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Common-Cause Failure Event Insights

Emergency Diesel Generators

Idaho National Engineering and Environmental Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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ABSTRACT

This report documents a study performed on the set of common-cause failures (CCF) of emergency diesel generators (EDG) from 1980 to 2000. The data studied here were derived from the NRC CCF database, which is based on US commercial nuclear power plant event data. This report is the result of an in-depth review of the EDG CCF data and presents several insights about the EDG CCF data. The objective of this document is to look beyond the CCF parameter estimates that can be obtained from the CCF data, to gain further understanding of why CCF events occur and what measures may be taken to prevent, or at least mitigate the effect of, EDG CCF events. This report presents quantitative presentation of the EDG CCF data and discussion of some engineering aspects of the EDG events.

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EXECUTIVE SUMMARY

This report provides insights related to emergency diesel generator (EDG) common-cause failure (CCF) events. These events were obtained from the U.S. Nuclear Regulatory Commission's (NRC) CCF Database. The EDG CCF data contains attributes about events that are of interest in the understanding of: completeness of the failures, occurrence rate trends of the events, EDG sub-system affected, causal factors, coupling or linking factors, event detection methods, and EDG manufacturer. Distributions of these CCF characteristics and trends were analyzed and individual events were reviewed for insights.

General Insights. The study identified 138 events occurring at U.S. nuclear power plant units during the period from 1980 through 2000. Forty-two units each had one CCF event during the period; 34 units did not experience a CCF event. The zero and one CCF event counts account for about 70 percent of the units. Seventeen percent of the units have experienced three or more EDG CCF events. There are no repeated failures in the EDG CCF events; each event is basically unique. Of the 138 events, 22 (16 percent) were Complete common-cause failures (failures events with all components failed due to a single cause in a short time).

Failure Modes. The events were classified as either failure to start or failure to run. The failure mode for the majority of the EDG CCF events is fail-to-run (57 percent). The fail-to-start failure mode accounted for the other 43 percent of the events.

Trends. Figure ES-1 shows the trend for all EDG CCF events. The decreasing trend for all EDG CCF events is statistically significant with a p-value of 0.0005. Based on the review of failure data for this study, improved maintenance and operating procedures, as well as increased maintenance focus and emphasis on equipment reliability from initiatives throughout the industry (NRC, utilities, INPO, and EPRI), appear to be reasons for the observed reduction of the occurrence of CCF events over the 21 years of experience included in this study. The failure mode trends were similar. The trend for the Complete events from 1980-2000 is decreasing and is statistically significant with a p-value = 0.0001. However, the trend from 1985-2000 is not statistically significant (p-value = 0.4874).

Method of Discovery. When the method of discovery was investigated, Testing accounted for 90 events (65 percent), Inspection for 28 events (20 percent), 12 events (9 percent) were discovered during an actual Demand, and eight events (6 percent) were discovered during Maintenance activities. These results are as expected considering the extensive and frequent surveillance test requirements for EDGs contained in Technical Specifications.

Proximate Cause. As shown in Figure ES-2, the leading proximate cause group was Design/Construction/Installation/Manufacture Inadequacy and accounted for about 33 percent of the total events. Internal to Component cause group accounted for 30 percent of the total. Operational/Human error cause group accounted for 22 percent of the total events, but contributed the largest number of Complete events (9 events, 41 percent).

The Design/Construction/Installation /Manufacture Inadequacy proximate cause group is the most likely for the EDGs and encompasses events related to the design, construction, installation, and manufacture of components, both before and after the plant is operational. Included in this category are events resulting from errors in equipment and system specifications, material specifications, and calculations. Events related to maintenance activities are not included.

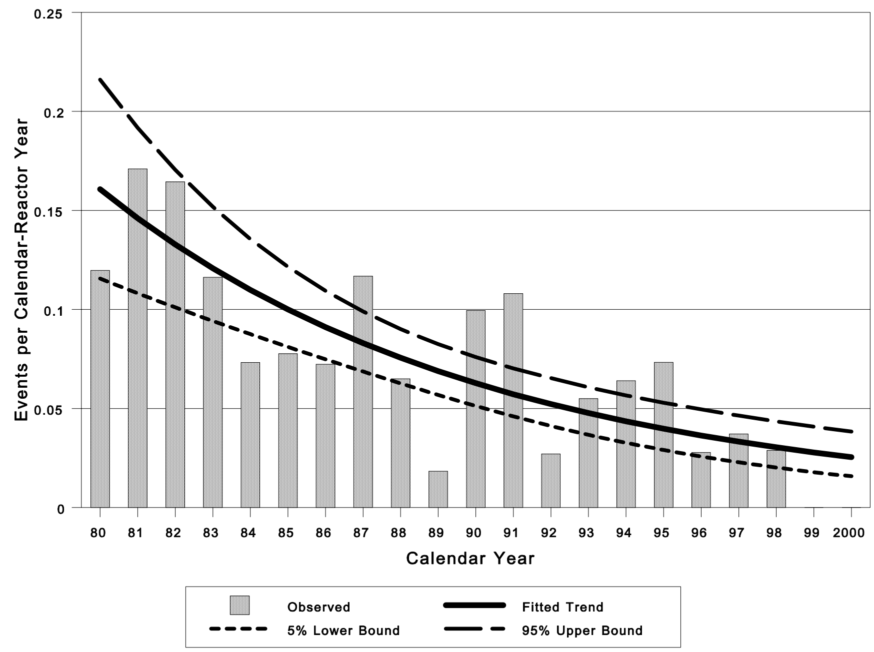

Figure ES-1. Trend for all EDG CCF events. The decreasing trend is statistically significant with a p-value = 0.0001.

The Internal to Component proximate cause category is important for the EDGs and encompasses the malfunctioning of hardware internal to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms that are influenced by the ambient environment of the component. Specific mechanisms include erosion, corrosion, internal contamination, fatigue, wear-out, and end of life.

The Operational/Human Error proximate cause group is the next most likely for the EDG and represents causes related to errors of omission or commission on the part of plant staff or contractor staff. Included in this category are accidental actions, failures to follow the correct procedures or following inadequate procedures for construction, modification, operation, maintenance, calibration, and testing. This proximate cause group may also include deficient training.

Coupling Factors. Design is the leading coupling factor with 66 events (48 percent). Design coupling factors result from common characteristics among components determined at the design level. Maintenance, with 39 events (28 percent), accounts for majority of the remaining events. These two coupling factors account for the top 76 percent of the events.

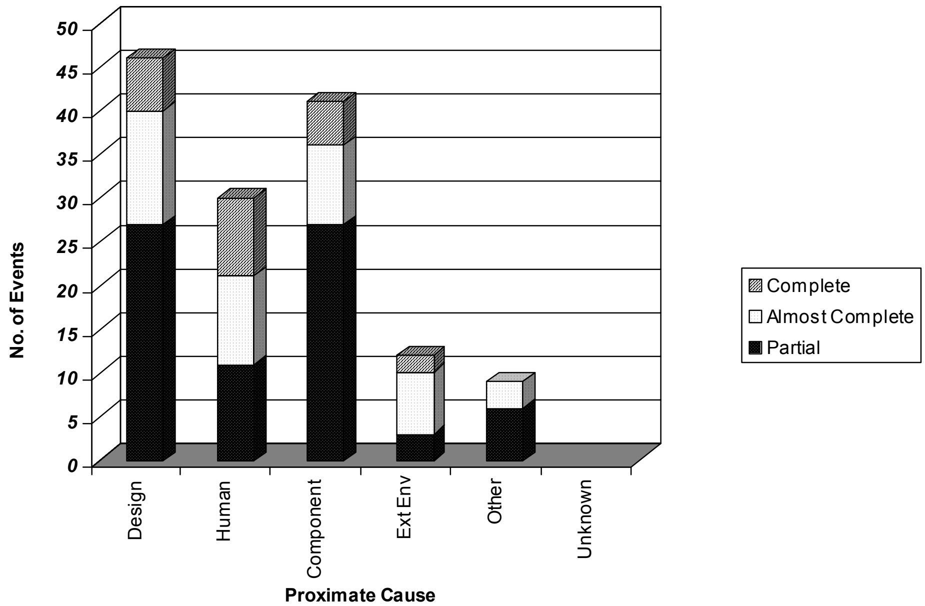

Figure ES-2. Proximate cause distribution for all EDG CCF events.

Sub-System. Figure ES-3 shows the distribution of EDG CCF events by affected sub-system. The majority of the EDG CCF events originated in the instrumentation and control sub-system. Cooling, engine, fuel oil, and generator each contribute significantly to the EDG CCF events. These five sub-systems contribute over 80 percent of the EDG CCF events. The cooling and engine sub-systems become much less significant and the instrumentation and control sub-systems become much more significant in the Complete set. The instrumentation and control sub-system is a complicated and diverse system that contains the functions of shutdown and control. Therefore, small errors in the instrumentation and control sub-system can propagate into Complete failures of the EDG component.

EDG Manufacturer. With respect to EDG manufacturer, the data show that the number of CCF events is independent of the manufacturer. A statistical test was performed to determine whether the occurrence of CCF events was independent of the manufacturer. The test was not statistically significant (p-value = 0.365).

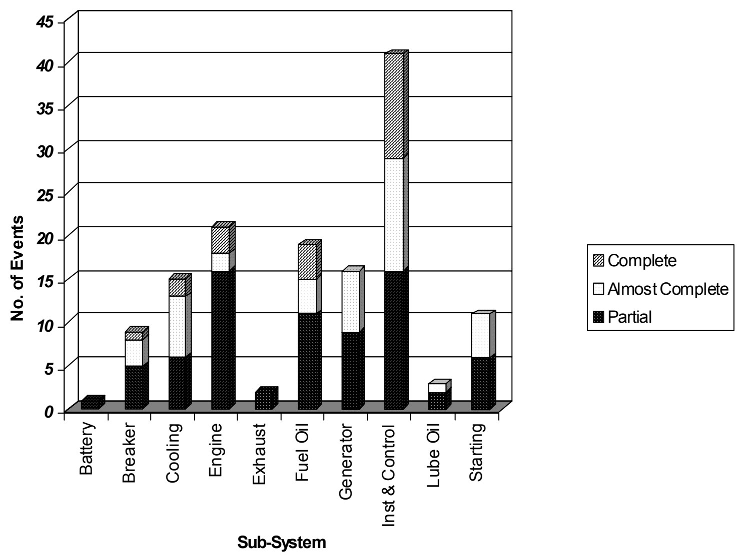

Figure ES-3. Distribution of EDG events by the affected sub-system.

Foreign EDG Experience. Most of the European EDG configurations involve either two or four EDGs. In many of the categories discussed above, the European EDG events are similar to the U.S. events, e.g., failure modes, method of discovery, and proximate cause. Some interesting points from the comparison are the following:

- When all events are considered, the human error category is much higher for the European events than the U.S. events. When only the Complete events are considered, the comparison is much closer with the human error being the most important for both. Design is an important proximate cause for both.

- Testing is overwhelmingly the most important method of discovery for both the European and U.S. EDG.

- The instrumentation and control sub-system contributes less when all events are considered for the European data than the USA data. Other important sub-systems for the European events are the fuel oil sub-system and the engine subsystem. When restricted to the Complete CCF events, the instrumentation and control sub-system is the most important for both groups; the fuel oil sub-system is the next most important. The fuel oil sub-system is also important for the Complete European events.

FOREWORD

This report provides common-cause failure (CCF) event insights for emergency diesel generators (EDGs). The results, findings, conclusions, and information contained in this study, the initiating event update study, and related system reliability studies conducted by the Office of Nuclear Regulatory Research support a variety of risk-informed NRC activities. These include providing information about relevant operating experience that can be used to enhance plant inspections of risk-important systems, and information used to support staff technical reviews of proposed license amendments, including risk-informed applications. In addition, this work will be used in the development of enhanced performance indicators that will be based largely on plant-specific system and equipment performance.

Findings and conclusions from the analyses of the EDG CCF data, which are based on 1980-2000 operating experience, are presented in the Executive Summary. High-level insights of all the EDG CCF data are presented in Section 3. Section 4 summarizes the events by sub-system. Section 5 presents EDG CCF insights from foreign experience. Section 6 provides information about how to obtain more detailed information for the EDG CCF events. The information to support risk-informed regulatory activities related to the EDG CCF data is summarized in Table F-1. This table provides a condensed index of risk-important data and results presented in discussions, tables, figures, and appendices.

Table F-1. Summary of Insights from Emergency Diesel Generator Common-Cause Failure Events.

Item	Description	Text Reference	Page(s)	Data
1.	CCF trends overview	Section 3.2	14	Figure 3-1 – Figure 3-4
2.	CCF sub-system overview	Section 3.3	17	Figure 3-5
3.	CCF proximate cause overview	Section 3.4	17	Figure 3-6
4.	CCF coupling factor overview	Section 3.5	20	Figure 3-7
5.	CCF discovery method overview	Section 3.6	22	Figure 3-8
6.	Engineering Insights – Instrumentation and Control	Section 4.2	29	Figure 4-1 – Figure 4-3
7.	Engineering Insights - Engine	Section 4.3	33	Figure 4-4 – Figure 4-6
8.	Engineering Insights – Fuel Oil	Section 4.4	36	Figure 4-7 – Figure 4-9
9.	Engineering Insights - Generator	Section 4.5	39	Figure 4-10 – Figure 4-12
10.	Engineering Insights - Cooling	Section 4.6	41	Figure 4-13 – Figure 4-15
11.	Engineering Insights – Starting Air	Section 4.7	44	Figure 4-16 –Figure 4-18
12.	Engineering Insights – Output Circuit Breaker	Section 4.8	47	Figure 4-19 –Figure 4-21
13.	Engineering Insights – Lubricating Oil	Sections 4.9	49	
14.	Engineering Insights – Exhaust	Section 4.10	49	
15.	Engineering Insights – Battery	Sections 4.11	50	
16.	EDG Foreign Experience	Section 5	51	
17.	Data Summaries	Appendix A and B		

The application of results to plant-specific applications may require a more detailed review of the relevant Licensee Event Report (LER) and Nuclear Plant Reliability Data System (NPRDS) or Equipment Performance Information and Exchange System (EPIX) data cited in this report. This review is needed to determine if generic experiences described in this report and specific aspects of the EDG CCF events documented in the LER and NPRDS failure records are applicable to the design and operational features at a specific plant or site. Factors such as system design, specific EDG components installed in the system, and test and maintenance practices would need to be considered in light of specific information provided in the LER and NPRDS failure records. Other documents such as logs, reports, and inspection reports that contain information about plant-specific experience (e.g., maintenance, operation, or surveillance testing) should be reviewed during plant inspections to supplement the information contained in this report.

Additional insights may be gained about plant-specific performance by examining the specific events in light of overall industry performance. In addition, a review of recent LERs and plant-specific component failure information in NPRDS or EPIX may yield indications of whether performance has undergone any significant change since the last year of this report. NPRDS archival data (through 1996) and EPIX failure data are proprietary information that can be obtained from the EPIX database through the Institute of Nuclear Power Operations (INPO). NRC staff and contractors can access that information through the EPIX database.

Common-cause failures used in this study were obtained from the common-cause failure database maintained for the NRC by the INEEL. NRC staff and contractors can access the plant-specific CCF information through the CCF database that is available on CD-ROM and has been provided to the NRC Regions and NRC Office of Nuclear Reactor Regulation (NRR). To obtain access to the NRC CCF Database, contact Dale Rasmuson [dmr@nrc.gov; (301) 415-7571] at the NRC or S. Ted Wood at the INEEL [stw@inel.gov; (208) 526-8729].

Periodic updates to the information in this report will be performed, as additional data become available. In the future, these insights will be available on the RES internal web page.

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ACRONYMS

ac	alternating current
CCCG	common-cause failure component group
CCF	common-cause failure
dc	direct current
ECCS	emergency core cooling system
EDG	emergency diesel generator
EPIX	equipment performance and information exchange
FTR	fail-to-run
FTS	fail-to-start
GI	generic issue
I&C	instrumentation and control
ICDE	international common-cause data exchange
INEEL	Idaho National Engineering and Environmental Laboratory
INPO	Institute of Nuclear Power Operations
IPE	individual plant examination
LER	licensee event report
LOCA	loss of coolant accident
LOSP	loss-of-offsite power
MCC	motor control center
NPP	nuclear power plant
NPRDS	Nuclear Plant Reliability Data System
NRC	Nuclear Regulatory Commission
PRA	probabilistic risk assessment
SBO	station blackout
SCSS	Sequence Coding and Search System
SIAS	safety injection actuation system
USI	unresolved safety issue

GLOSSARY

Application—A particular set of CCF events selected from the common-cause failure database for use in a specific study.

Average Impact Vector—An average over the impact vectors for different hypotheses regarding the number of components failed in an event.

Basic Event—An event in a reliability logic model that represents the state in which a component or group of components is unavailable and does not require further development in terms of contributing causes.

Common-cause Event—A dependent failure in which two or more component fault states exist simultaneously, or within a short time interval, and are a direct result of a shared cause.

Common-cause Basic Event—In system modeling, a basic event that represents the unavailability of a specific set of components because of shared causes that are not explicitly represented in the system logic model as other basic events.

Common-cause Component Group—A group of (usually similar [in mission, manufacturer, maintenance, environment, etc.]) components that are considered to have a high potential for failure due to the same cause or causes.

Common-cause Failure Model—The basis for quantifying the probability of common-cause events. Examples include the beta factor, alpha factor, basic parameter, and the binomial failure rate models.

Component—An element of plant hardware designed to provide a particular function.

Component Boundary—The component boundary encompasses the set of piece parts that are considered to form the component.

Component Degradation Value—The assessed probability ($0.0 \leq p \leq 1.0$) that a functionally- or physically-degraded component would fail to complete the mission.

Component State—Component state defines the component status in regard to its intended function. Two general categories of component states are defined, available, and unavailable.

> *Available*—The component is available if it is capable of performing its function according to a specified success criterion. (N.B., available is not the same as availability.)
>
> *Unavailable*—The component is unavailable if the component is unable to perform its intended function according to a stated success criterion. Two subsets of unavailable states are failure and functionally unavailable.

Coupling Factor/Mechanism—A set of causes and factors characterizing why and how a failure is systematically induced in several components.

Date—The date of the failure event, or date the failure was discovered.

Defense—Any operational, maintenance, and design measures taken to diminish the probability and/or consequences of common-cause failures.

Degree of Failure— The Degree of Failure category has three groups: Complete, Almost Complete, and Partial. The degree of failure is a categorization of a CCF event by the magnitude of three quantification parameters: component degradation value, shared cause factor, and timing factor. These parameters can be given values from zero to 1.0. The degree of failure categories are defined as follows:

> *Complete*—A common-cause failure in which all redundant components are failed simultaneously as a direct result of a shared cause; i.e., the component degradation value equals 1.0 for all components, and both the timing factor and the shared cause factor are equal to 1.0.
>
> *Almost Complete*—A common-cause failure in which one of the parameters is not equal to 1.0. Examples of events that would be termed Almost Complete are: events in which most components are completely failed and one component is degraded, or all components are completely failed but the time between failures is greater than one inspection interval.
>
> *Partial*—All other common-cause failures (i.e., more than one of the quantification parameters is not equal to 1.0.)

Dependent Basic Events—Two or more basic events, A and B, are statistically dependent if, and only if,

$$P[A \cap B] = P[B \mid A]P[A] = P[A \mid B]P[B] \neq P[A]P[B],$$

where P[X] denotes the probability of event X.

Event—An event is the occurrence of a component state or a group of component states.

Exposed Population—The set of components within the plant that are potentially affected by the common-cause failure event under consideration.

Failure—The component is not capable of performing its specified operation according to a success criterion.

Failure Mechanism—The history describing the events and influences leading to a given failure.

Failure Mode—A description of component failure in terms of the component function that was actually or potentially unavailable.

Failure Mode Applicability—The analyst's probability that the specified component failure mode for a given event is appropriate to the particular application.

Functionally Unavailable—The component is capable of operation, but the function normally provided by the component is unavailable due to lack of proper input, lack of support function from a source outside the component (i.e., motive power, actuation signal), maintenance, testing, the improper interference of a person, etc.

Impact Vector—An assessment of the impact an event would have on a common-cause component group. The impact is usually measured as the number of failed components out of a set of similar components in the common-cause component group.

Independent Basic Events—Two basic events, A and B, are statistically independent if, and only if,

$$P[A \cap B] = P[A]P[B],$$

where P[X] denotes the probability of event X.

Mapping—The impact vector of an event must be “mapped up” or “mapped down” when the exposed population of the target plant is higher or lower than that of the original plant that experienced the common-cause failure. The result of mapping an impact vector is an adjusted impact vector applicable to the target plant.

Mapping Up Factor—A factor used to adjust the impact vector of an event when the exposed population of the target plan is higher than that of the original plant that experienced the common-cause failure.

P-Value—A p-value is a probability, that indicates a measure of statistical significance. The smaller the p-value, the greater the significance. A p-value of less than 0.05 is generally considered statistically significant.

Potentially Unavailable—The component is capable of performing its function according to a success criterion, but an incipient or degraded condition exists. (N.B., potentially unavailable is not synonymous with hypothetical.)

> *Degraded*—The component is in such a state that it exhibits reduced performance but insufficient degradation to declare the component unavailable according to the specified success criterion.
>
> *Incipient*—The component is in a condition that, if left un-remedied, could ultimately lead to a degraded or unavailable state.

Proximate Cause—A characterization of the condition that is readily identified as leading to failure of the component. It might alternatively be characterized as a symptom.

Reliability Logic Model—A logical representation of the combinations of component states that could lead to system failure. A fault tree is an example of a system logic model.

Root Cause—The most basic reason for a component failure, which, if corrected, could prevent recurrence. The identified root cause may vary depending on the particular defensive strategy adopted against the failure mechanism.

Shared-Cause Factor (c)—A number that reflects the analyst’s uncertainty ($0.0 \leq c \leq 1.0$) about the existence of coupling among the failures of two or more components, i.e., whether a shared cause of failure can be clearly identified.

Shock—A shock is an event that occurs at a random point in time and acts on the system; i.e., all the components in the system simultaneously. There are two kinds of shocks distinguished by the potential impact of the shock event, i.e., lethal and nonlethal.

Statistically Significant—The term "statistically significant" means that the data are too closely correlated to be attributed to chances and consequently have a systematic relationship.

System—The entity that encompasses an interacting collection of components to provide a particular function or functions.

Timing Factor (q) —The probability ($0.0 \le q \le 1.0$) that two or more component failures (or degraded states) separated in time represent a common-cause failure. This can be viewed as an indication of the strength-of-coupling in synchronizing failure times.

Common-Cause Failure Event Insights for Emergency Diesel Generators

1. INTRODUCTION

This report presents insights about the common-cause events that have occurred in the emergency diesel generator (EDG) system at operating nuclear power plants. The focus is on commercial nuclear power plants operating in the United States but highlights are also presented for international nuclear power plants.

The insights for the U.S. plants are derived from information captured in the common-cause failure (CCF) database maintained for the Nuclear Regulatory Commission (NRC) by the Idaho National Engineering and Environmental Laboratory (INEEL). The database contains CCF-related events that have occurred in U.S. commercial nuclear power plants reported in licensee event reports (LERs) and reports to the Nuclear Plant Reliability Data System (NPRDS) and the Equipment Performance Information Exchange (EPIX) system maintained by the Institute for Nuclear Power Operations (INPO)

The information presented in this report is intended to help focus NRC inspections on the more risk-important aspects of EDG CCF events. Utilities can also use the information to help focus maintenance and test programs such that EDG CCF events are minimized.

1.1 Background

The following four criteria must be met for an event to be classified as resulting from a common-cause:

- Two or more individual components must fail or be degraded, including failures during demand, inservice testing, or from deficiencies that would have resulted in a failure if a demand signal had been received;

- Two or more individual components must fail or be degraded in a select period of time such that the probabilistic risk assessment (PRA) mission would not be certain;

- The component failures or degradations must result from a single shared cause and coupling mechanism; and

- The component failures are not due to the failure of equipment outside the established component boundary.

To help resolve NRC Generic Issue 145, [1] *Actions to Reduce Common-Cause Failures*, and to address deficiencies related to the availability and analysis of CCF data, the NRC and the INEEL developed a CCF database that codifies information on CCF-related events that have occurred in U.S. commercial nuclear power plants from 1980 to date. The data is derived from both licensee event reports (LERs) submitted to the NRC and equipment performance reports submitted to the INPO. Accompanying the development of the CCF database was the development of CCF analysis software for investigating the CCF aspect of system reliability analyses and related risk-informed applications.

The quantitative results of this CCF data collection effort are described in the four volumes of NUREG/CR-6268, *Common-Cause Failure Database and Analysis System*.[2,3,4,5] Some quantitative insights about the data for use in PRA studies were also published in NUREG/CR-5497,[6] *Common-Cause Failure Parameter Estimations*. Copies of the CCF database together with supporting technical documentation and the analysis software are available on CD-ROM from the NRC to aid in system reliability analyses and risk-informed applications.

The CCF event data collected, classified, and compiled in the CCF database provide a unique opportunity to go beyond just estimation of CCF probabilities but to also gain more engineering insights into how and why CCF events occur. The data classification employed in the database was designed with this broader objective in mind. The data captured includes plant type, system component, piece parts, failure causes, mechanisms of propagation of failure to multiple components, their functional and physical failure modes. Other important characteristics such as defenses that could have prevented the failures are also included.

Section 1.2 of Volume 3 of NUREG/CR-6268 (Reference 4) proposes methods for classifying common-cause failures using the concepts of causes, coupling factors, and defensive mechanisms. The methods suggest a causal picture of failure with an identification of a root cause, a means by which the cause is more likely to impact a number of components simultaneously (the coupling), and the failure of the defenses against such multiple failures. Utilizing these methods, the CCF data associated with EDGs were analyzed to provide a better understanding of EDG CCFs. This report presents the results of this effort.

The data analyzed are derived from the CCF database. The coding and quality assurance (QA) process for entering data into the database is as follows: Each event is coded from an LER or an NPRDS or EPIX report by analysts at the INEEL. Each analyst has access to coding guidelines (NUREG/CR-6268), which provides specific direction to the analyst about what the required information means and how to enter the information into the database. Each analyst is knowledgeable about PRA and plant systems and operations. Each event is initially coded by one analyst and reviewed by another analyst with a comparable background. Any disagreement is resolved before coding of the event is considered completed. An additional review of the events is done by another person familiar with PRA and CCF concepts. An independent outside expert in CCF and PRA then reviews the coding. Any differences are resolved and the final coding changes made in the database. The data collection, analysis, independent review, and quality assurance process are described in more detail in NUREG/CR-6268, Volumes 1 and 3 (References 2 and 4).

1.2 Common-Cause Failure Event Concepts

CCFs can be thought of as resulting from the coexistence of two main factors: one that provides a susceptibility for components to fail or become unavailable due to a particular cause of failure and a coupling factor (or coupling mechanism) that creates the condition for multiple components to be affected by the same cause.

An example is a case where two relief valves fail-to-open at the required pressure due to set points being set too high. Because of personnel error (the proximate cause), each of the two valves fails due to an incorrect setpoint. What makes the two valves fail together, however, is a common calibration procedure and common maintenance personnel. These commonalties are the coupling factors of the failure event in this case.

Characterization of CCF events in terms of these key elements provides an effective means of performing engineering assessments of the CCF phenomenon including approaches to identification of plant vulnerabilities to CCFs and evaluation of the need for, and effectiveness of, defenses against them.

It is equally effective in evaluation and classification of operational data and quantitative analysis of CCF frequencies.

It is evident that each component fails because of its susceptibility to the conditions created by the root cause, and the role of the coupling factor is to make those conditions common to several components. In analyzing failure events, the description of a failure in terms of the most obvious "cause" is often too simplistic. The sequence of events that constitute a particular failure mechanism is not necessarily simple. Many different paths by which this ultimate reason for failure could be reached exist. This chain can be characterized by two useful concepts— proximate cause and root cause.

The proximate cause of a failure event is the condition that is readily identifiable as leading to the failure. The proximate cause can be regarded as a symptom of the failure cause, and it does not in itself necessarily provide a full understanding of what led to that condition. As such, it may not be the most useful characterization of failure events for the purposes of identifying appropriate corrective actions. The proximate cause classification consists of six major categories:

- Design, construction, installation, and manufacture inadequacy causes,
- Operational and human-related causes (e.g. procedural errors, maintenance errors),
- Internal to the component, including hardware-related causes and internal environmental causes,
- External environmental causes,
- State of other component, and
- Other causes.

The causal chain can be long and, without applying a criterion identifying an event in the chain as a "root cause," is often arbitrary. Identifying root causes in relation to the implementation of defenses is a useful alternative. The root cause is therefore the most basic reason or reasons for the component failure, which if corrected, would prevent recurrence. Volume 3 of NUREG/CR-6268 (Reference 4) contains additional details on the cause categories and how CCF event causes are classified.

The coupling factor is a characteristic of a group of components or piece parts that identifies them as susceptible to the same causal mechanisms of failure – it is a characteristic that links the components. Such factors include similarity in design, location, environment, mission, and operational, maintenance, and test procedures. Coupling factors are categorized into the following five groups for analysis purposes:

- Hardware Quality,
- Hardware Design,
- Maintenance,
- Operations, and
- Environment.

Note that proximate causes of CCF events are no different from the proximate causes of single component failures.

The proximate causes and the coupling factors may appear to overlap because the same name is sometimes used as a proximate cause and as a coupling factor (e.g., design, maintenance). However, they are different. For example, maintenance, as a proximate cause, refers to errors and mistakes made during maintenance activities. As a coupling factor, maintenance refers to the similarity of maintenance among the components (e.g., same maintenance personnel, same maintenance procedures).

The defense or defensive mechanism is any operational, maintenance, or design measure taken to diminish the probability and/or consequences of a common-cause failure event. Three ways of defending against a CCF event are the following: (1) defend against the failure proximate cause, (2) defend against the coupling factor, or (3) defend against both the proximate cause and the coupling factor. As an example, consider two redundant components in the same room as a steam line. A barrier that separates the steam line from the components is an example of defending against the proximate cause. A barrier that separates the two components is an example of defending against the coupling factor (same location). Installing barriers around each component is an example of defending against both the cause and the coupling factor.

Proximate causes of CCF events are no different from the proximate causes of single component failures. This observation suggests that defending against single component failures can have an impact on CCFs as well. Most corrective actions usually attempt to reduce the frequency of failures (single or multiple). That is, very often the approach to defending against CCFs is to defend against the cause, not the coupling. Given that a defensive strategy is established based on reducing the number of failures by addressing proximate causes, it is reasonable to postulate that if fewer component failures occur, fewer CCF events would occur.

Defenses against causes result in improving the reliability of each component but do not necessarily reduce the fraction of failures that occur due to common-cause. They typically include design control, use of qualified equipment, testing and preventive maintenance programs, procedure review, personnel training, quality control, redundancy, diversity, and barriers. It is important to remember that the susceptibility of a system of redundant components to dependent failures as opposed to independent failures is determined by the presence of coupling factors.

The above cause-defense approach does not address the way that failures are coupled. Therefore, CCF events can occur, but at a lower probability. If a defensive strategy is developed using protection against a coupling factor as a basis, the relationship among the failures is eliminated. A search for coupling factors is primarily a search for similarities among components. A search for defenses against coupling, on the other hand, is primarily a search for dissimilarities among components, including differences in the components themselves (diversity); differences in the way they are installed, operated, and maintained; and in their environment and location.

During a CCF analysis, a defense based on a coupling factor is easier to assess because the coupling mechanism among failures is more readily apparent and therefore easier to interrupt. The following defenses are oriented toward eliminating or reducing the coupling among failures: diversity, physical or functional barriers, and testing and maintenance policies. A defensive strategy based on addressing both the proximate cause and coupling factor would be the most comprehensive.

A comprehensive review should include identification of the root causes, coupling factors, and defenses in place against them. However, as discussed in NUREG/CR-5460,[7] *A Cause-Defense Approach to the Understanding and Analysis of Common-Cause Failures*, given the rarity of common-cause events, current weaknesses of event reporting and other practical limitations, approaching the problem from the point of view of defenses is, perhaps, the most effective and practical. A good defense can prevent a whole class of CCFs for many types of components, and in this way, the application of a procedure based on this philosophy can provide a systematic approach to screening for potential CCF mechanisms.

1.3 Report Structure

This report presents an overview of the EDG CCF data and insights into the characteristics of that data. This report is organized as follows: Section 2 presents a description of the EDG, a short description of the associated sub-systems, and a definition of the EDG failure modes. High level insights of all the EDG CCF data are presented in Section 3. Section 4 summarizes the events by subsystem. Section 5 presents EDG CCF insights from the International Common-Cause Data Exchange (ICDE) Project. Section 6 provides information about how to obtain more detailed information for the EDG events. A glossary of terms is included in the front matter. Appendix A contains three listings of the EDG CCF events sorted by proximate cause, coupling factor, and discovery method. Appendix B contains a listing of the EDG CCF events sorted by the sub-system.

2. COMPONENT DESCRIPTION

2.1 Introduction

The emergency diesel generators (EDGs) are part of the Class 1E AC electrical power distribution system providing reliable emergency power to electrical buses that supply the emergency core cooling system (ECCS) and various other equipment necessary for a safe shutdown of the reactor. In general, each EDG configuration ensures that adequate electrical power is available in a postulated loss-of-offsite power (LOSP) event; with or without a concurrent large break loss-of-coolant accident (LOCA). Gas turbine generators and hydroelectric generators (used at some locations for emergency power) are not part of this study. High-pressure core spray diesels are considered (for this study) to be a separate train of the emergency AC power system. Diesel engines used for fire pumps, fire protection as per 10 CFR 50 Appendix R, or non-Class 1E backup generators are not included.

The EDGs are normally in standby, whether the plant is at power or shutdown. At least one EDG is required by Technical Specifications to be aligned to provide emergency power to safety-related electrical buses in case of a LOSP at the plant. In some cases a "swing" EDG is used that can supply power to more than one unit (but not simultaneously) such that two units will have a total of only three EDGs; one EDG dedicated to each specific power plant, and a swing EDG capable of powering either plant. Electrical load shedding (intentional load removal) of the safety bus and subsequent sequencing of required loads after closure of the EDG output breaker is considered part of the EDG function. The EDG system is automatically actuated by signals that sense either a LOCA or a degradation of electrical power to its safety bus. The EDG can be started manually from the control room.

2.2 Risk Significance

A station blackout is the total loss of alternating current (ac) electrical power to the essential and nonessential equipment at a nuclear power plant. Station blackout involves the loss of offsite power concurrent with the failure of the onsite emergency power system. Because many safety systems required for reactor core cooling, decay heat removal, and containment heat removal depend on ac power, the consequences of station blackout could be severe. If a station blackout occurred and ac power was not recovered, it would ultimately result in core damage. The Individual Plant Examinations (IPEs) showed that station blackout is a significant contributor to core damage frequency for most U.S. nuclear power plants.[8] Failure of EDGs, including common-cause failure, is one important factor. EDGs are less important in BWRs due to the greater number of safety systems that can function during a SBO (i.e., reactor core isolation cooling (RCIC), high pressure coolant injection (HPCI), and high pressure core spray (HPCS)).

2.3 Component Description and Boundary

In this analysis, the EDG is defined as the combination of the diesel engine with all components in the exhaust path, electrical generator, generator exciter, output breaker, combustion air, lube oil systems, cooling system, fuel oil system, and the starting compressed air system. All pumps, valves, and valve operators with their power supply breakers and associated piping for the above systems are included. The only portions of the EDG cooling systems included were the specific devices that control cooling medium flow to the individual EDG auxiliary heat exchangers, including the control instruments. The service water system (cooling medium) outside the control valves was excluded. The EDG room ventilation was included if the licensee reported ventilation failures that affected EDG functional operability. Figure 2-1 shows the component boundary as defined for this study.

Included within the EDG system are the circuit breakers that are located at the motor control centers (MCCs), and the associated power boards, that supply power specifically to any of the EDG equipment. The MCCs and the power boards are not included except for the load shedding and load sequencing circuitry/devices that are, in some cases, physically located within the MCCs. Load shedding of the safety bus and subsequent load sequencing onto the bus of vital electrical loads is considered integral to the EDG function and is therefore considered within the bounds of this study. All instrumentation, control logic, and the attendant process detectors for system initiations, trips, and operational control are included. Batteries were included if failures impacted EDG functional operability.

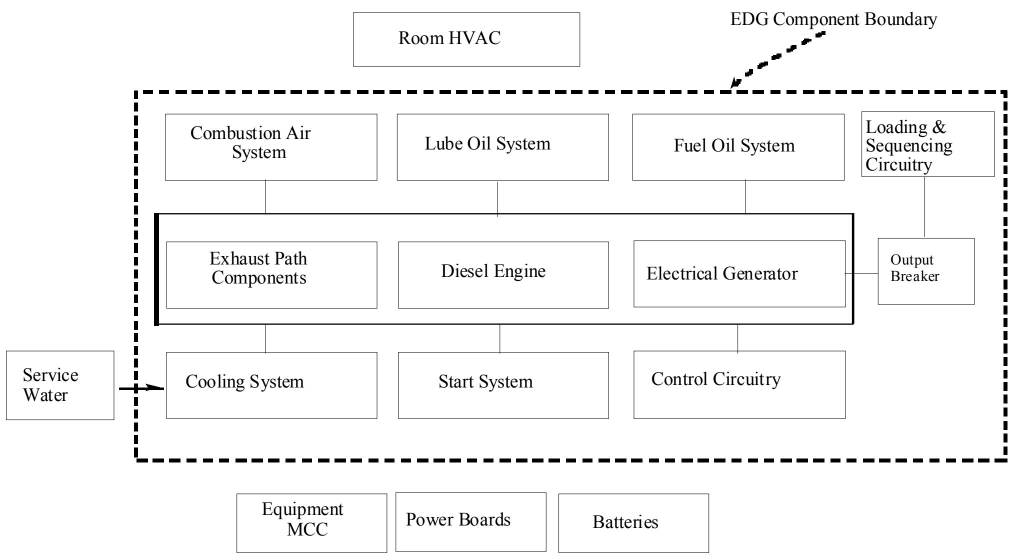

Figure 2-1. Emergency diesel generator component boundaries.

2.4 Sub-System Description

This section contains a brief description of each of the sub-systems that comprise the EDG. These descriptions are intended only to provide a general overview of the most common EDGs.

2.4.1 Battery

The battery sub-system serves as a DC power backup to the normal instrumentation and control (instrumentation and control) power supply.

2.4.2 Combustion Air

The combustion air sub-system receives air from the outside and passes it to the EDG through a filter and a damper.

2.4.3 Cooling

The cooling sub-system is a closed-loop water system integral to the engine and generator and has an external-cooling medium, typically, the plant emergency service water. The pumps, heat exchangers, and valves are considered part of this system. The cooling water jacket is considered part of the engine sub-system.

2.4.4 Engine

The engine sub-system is the physical engine block and piece-parts internal to it. These parts include pistons, crankshafts, turbochargers, cooling water jackets, and the governor. The engine governor maintains correct engine speed by metering the fuel oil to each cylinder injector.

2.4.5 Exhaust

The exhaust sub-system consists of the piping and valves installed to direct the engine exhaust out of the building.

2.4.6 Fuel Oil

The fuel oil sub-system provides fuel oil from large external storage tanks, having a capacity for several days of system operation, to a smaller day tank for each engine. The day tank typically has capacity to operate the engine for 4 to 6 hours. Day tank fuel is supplied to the cylinder injectors, which inject the fuel to each individual cylinder for combustion.

2.4.7 Generator

The generator sub-system consists of the generator casing, rotor, windings, and exciter, which all function to deliver electrical power to the output breaker.

2.4.8 Instrumentation and Control

The instrumentation and control sub-system components function to start, stop, and provide operational control and protective trips for the EDG. Controls for the EDGs are a mix of pneumatic and electrical devices, depending on the manufacturer. These function to control the voltage and speed of the EDG. Various trips for the engine and generator exist to protect the EDG. During the emergency start mode of operation, some of these protective trips associated with the EDG engine are bypassed.

The instrumentation and control sub-system also includes the loading and sequencing circuitry.[a] The automatic load shedding and sequencing circuitry controls the order and timing of emergency loads that are loaded onto the safety-related bus. The purpose of this equipment is to prevent the instantaneous full loading of the engine when the output circuit breaker is closed, such as by ECCS loads during a LOCA.

2.4.9 Lubrication Oil

The lubrication oil sub-system is a closed loop system integral to the engine and generator consisting of a sump, various pumps, and a heat exchanger.

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a. It should be noted that the definition of the EDG component boundary differs here from the definition provided in Regulatory Guide (RG) 1.9, *"Regulatory Effectiveness of the Station Blackout Rule"*. In RG 1.9, the EDG system boundary does not include the load sequencer or the bus between the EDG and its loads.

2.4.10 Output Circuit Breaker

The output circuit breaker sub-system includes the main EDG output circuit breaker.

2.4.11 Starting Air

The starting air sub-system consists of those components required to start the EDG. Typically, this system uses compressed air. The air start system provides compressed air to the engine through a system of valves, relief valves, air receivers, air motor, and a distributor.

2.5 Failure Modes

Successful EDG system response to a demand requires that the EDGs provide electrical power to the safety bus with all required loads energized (sequenced onto the bus) for the duration of the mission time. The failure modes used in evaluating the EDG data are:

Fail-to-start (FTS): A successful start will be the EDG start through output breaker closing and loading to the requirement for the current configuration. For example, if the start is in response to an actual loss of power, the full sequence of loading must be completed in order for the start to be considered successful. If only partial loading occurs before the failure, the failure mode will be fail-to-start. If the start requires no loading (e.g. a test or on a SI signal), the success criteria will be only the EDG start.

Fail-to-run (FTR): In order for the failure to be a failure to run, the EDG must be loaded (required for the current conditions) and stable before the failure. This failure mode implies a successful start, but a subsequent failure to run for the duration of the mission time.

The EDG failures represent malfunctions that hindered or prevented successful operation of the EDG system. Slow EDG starting times during testing were considered successful provided the start took less than 20 seconds and the EDG was otherwise fully capable. Most licensees reporting a slow start time provided additional analysis to indicate that the slow start time did not adversely affect the ability of the plant to respond to a design basis accident. Conditions related to potential failure due to seismic design, environmental qualification, or other similar concerns were not considered. Any EDG inoperabilities declared strictly for administrative reasons were not considered failures (e.g., a surveillance test not performed within the required time frame). Failures during troubleshooting or when the EDG would not reasonably be considered fully capable, such as after major maintenance, were also not considered failures. If a failure occurred on equipment other than what had been repaired during an operational surveillance test following maintenance, another failure was counted.

For purposes of this CCF study, a personnel error resulting in more than one functionally inoperable EDG (even without any component malfunction) was considered a CCF failure. Examples are improper pre-start lineup and significant setting errors in the governor or voltage regulator controls. These types of errors would have prevented fulfillment of the EDG system design function. On the other hand, operator error in such things as paralleling to the grid or improper adjustment of voltage or speed controls were not considered failures because these do not normally apply to an actual EDG demand.

Some CCF events affected the second unit of a multiple-unit site; if the report indicated that EDGs at the other unit(s) would have also failed for the same reason one CCF event was coded, with the CCCG value assigned as the total number of EDGs at the site. When a licensee modified the design or replaced parts on multiple EDGs (at a site) in response to the failure of a single component, the replaced components were considered to have failed. These events were coded as CCFs.

3. HIGH LEVEL OVERVIEW OF EMERGENCY DIESEL GENERATOR INSIGHTS

3.1 Introduction

This section provides an overview of CCF data for the EDG component that has been collected from the NRC CCF database. The set of EDG CCF events is based on industry data from 1980 to 2000. The EDG CCF data contains attributes about events that are of interest in the understanding of: degree of completeness, trends, EDG sub-system affected, causal factors, linking or coupling factors, event detection methods, and EDG manufacturer.

Not all EDG CCF events included in this study resulted in observed failures of multiple EDGs. Many of the events included in the database, in fact, describe degraded states of the EDGs where, given the conditions described, the EDGs may or may not have performed as required. The CCF guidance documents (References 3 and 4) allow the use of three different quantification parameters (component degradation value, shared cause factor, and timing factor) to measure degree of failure for CCF events. Based on the values of these three parameters, a Degree of Failure was assigned to each EDG CCF event.

The Degree of Failure category has three groups—Complete, Almost Complete, and Partial. Complete CCF events are CCF events in which each component within the common-cause failure component group (CCCG) fails completely due to the same cause and within a short time interval (i.e., all quantification parameters equal 1.0). Complete events are important since they show us evidence of observed CCFs of all components in a common-cause group. Complete events also dominate the parameter estimates obtained from the CCF database. All other events are termed partial CCF events (i.e., at least one quantification parameter is not equal to 1.0). A subclass of partial CCF events are those that are Almost Complete CCF events. Examples of events that would be termed Almost Complete are: events in which most components are completely failed and one component is degraded, or all components are completely failed but the time between failures is greater than one inspection interval (i.e., all but one of the quantification parameters equal 1.0).

Table 3-1 summarizes, by failure mode and degree of failure, the EDG CCF events contained in this study. The majority of the EDG CCF events were fail-to-run (57 percent). The review of the data suggests that many failures require the EDG to be running to develop failures and for those failures to be detected. The Complete degree of failure makes up a small fraction (16 percent) of the EDG CCF events. However, almost half (46 percent) of the events are classified as either Complete or Almost Complete.

Table 3-1. Summary statistics of EDG data.

Failure Mode	Degree of Failure			Total
	Partial	Almost Complete	Complete	
Fail-to-start (FTS)	29	20	10	59
Fail-to-run (FTR)	45	22	12	79
Total	74	42	22	138

3.2 CCF Trends Overview

Figure 3-1 shows the yearly occurrence rate, the fitted trend, and its 90 percent uncertainty bounds for all EDG CCF events over the time span of this study. The decreasing trend is statistically significant[b] with a p-value[c] of 0.0001. Based on the review of failure data for this study, the improved maintenance and operating procedures as well as the improved testing and inspection requirements have facilitated the observed reduction of the occurrence of CCF events over the 21 years of experience included in this study.

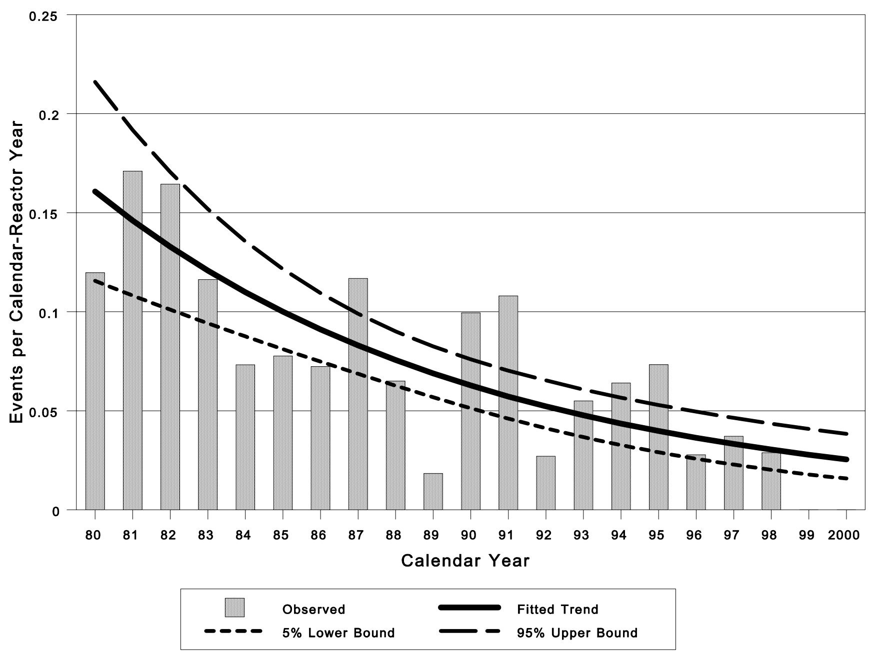

Figure 3-1. Trend for all EDG CCF events. The decreasing trend is statistically significant with a p-value = 0.0001.

Figure 3-2 through Figure 3-4 show trends for subsets of the EDG CCF events contained in Figure 3-1. Figure 3-2 shows the trend for Complete EDG CCF events. The overall trend from 1980 to 2000 is also statistically significant with a p-value of 0.0001. This indicates a dramatic decrease of Complete EDG CCF events, especially since the mid-1980's. However, since 1985, the occurrence rate of Complete EDG CCFs is essentially flat with a p-value of 0.4874. Figure 3-3 and Figure 3-4 show similar statistically significant decreasing trends for both the fail-to-start and the fail-to-run failure modes for all EDG CCF events, both with p-values of 0.0001.

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b. The term "statistically significant" means that the data are too closely correlated to be attributed to chances and consequently have a systematic relationship. A p-value of less than 0.05 is generally considered to be statistically significant.

c. A p-value is a probability, with a value between zero and one, which is a measure of statistical significance. The smaller the p-value, the greater the significance. A p-value of less than 0.05 is generally considered statistically significant. A p-value of less than 0.0001 is reported as 0.0001.

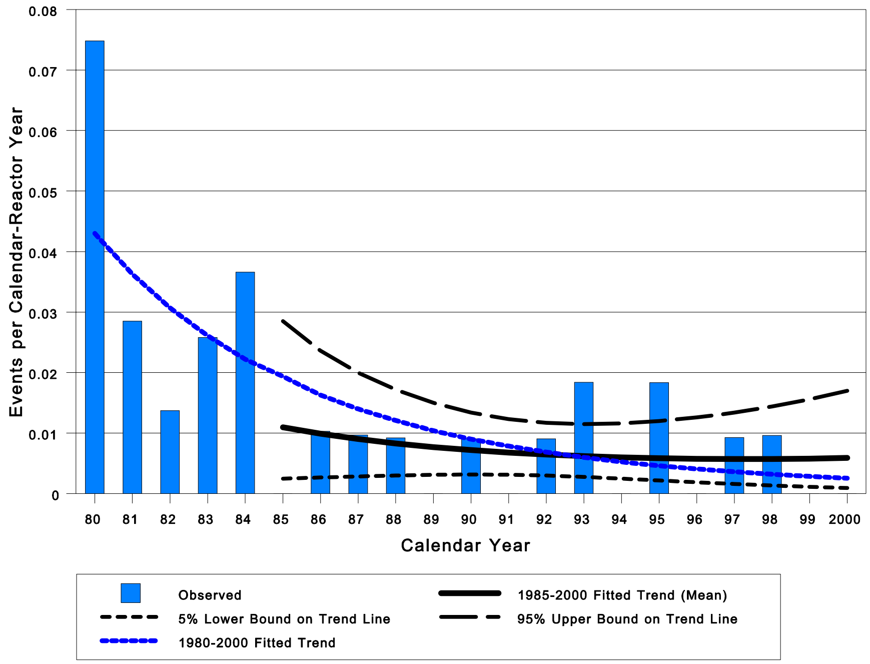

Figure 3-2. Trend for Complete EDG CCF events. The decreasing trend is statistically significant with a p-value = 0.0001. The trend from 1985-2000 is not statistically significant (p-value = 0.4874).

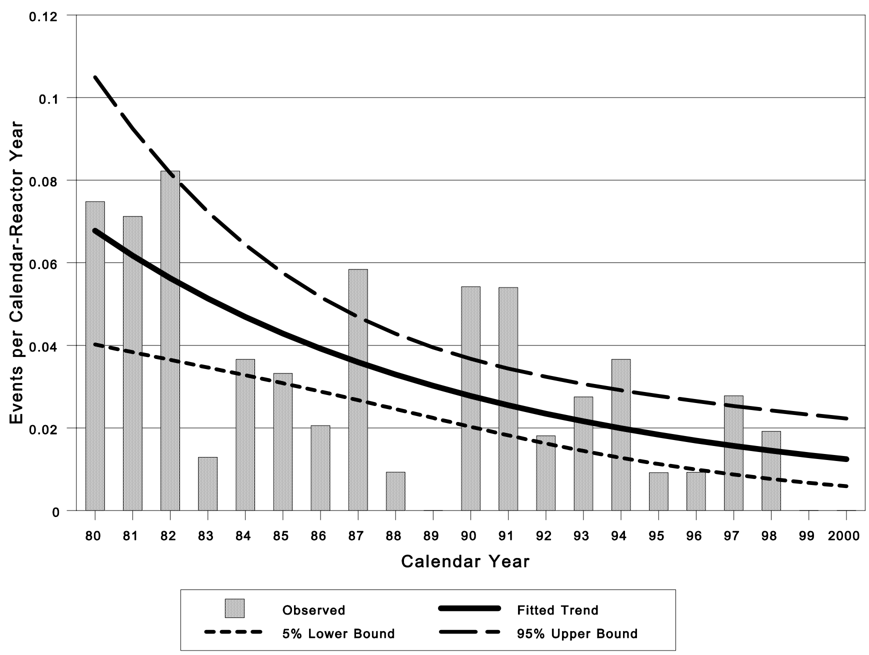

Figure 3-3. Trend for all EDG CCF events for the fail-to-start failure mode. The decreasing trend is statistically significant with a p-value = 0.0001

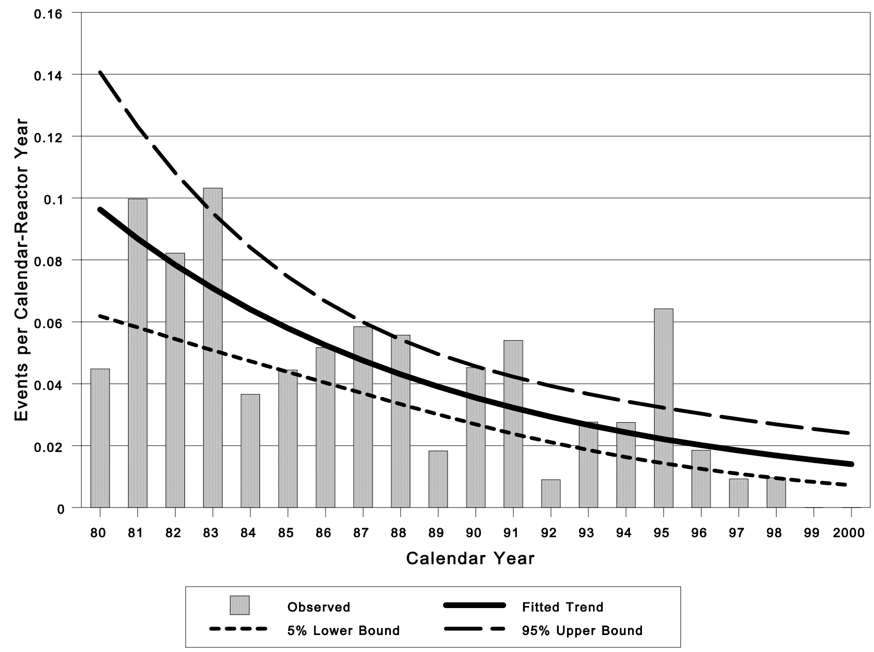

Figure 3-4. Trend for all EDG CCF events for the fail-to-run failure mode. The decreasing trend is statistically significant with a p-value = 0.0001.

In 1980, the NRC designated the issue of station blackout (SBO), which is a loss of all ac off-site and on-site power concurrent with a reactor trip, as Unresolved Safety Issue (USI) A-44. The goal of USI A-44 was to determine the need for additional safety requirements since SBO can be a significant contributor to core damage frequency. In 1988, the Commission concluded that additional SBO safety requirements were justified and issued the SBO rule (10 CFR 50.63).[9]

The SBO rule established an EDG reliability program that was to maintain the reliability of the EDG at or above 0.95. The EDG CCF data in this study suggest that the nuclear industry started improving the reliability of the EDGs prior to the final issue of the SBO rule in 1988. This effort appears to have significantly improved the CCF aspect of EDG reliability. A study on EDG reliability from 1987 to 1993[10] also found no increasing or decreasing trend in EDG failure rates over the period of that study.

In Figure 3-2, the bars at approximately 0.01 events per calendar-reactor year correspond to a single Complete EDG CCF event in the year and the bars at approximately 0.02 correspond to two Complete EDG CCF event in the year. To show a statically significant decrease in the occurrence of Complete EDG CCF events, there would have to be many years without any Complete EDG CCF events.

Since 1985, the majority of the Complete EDG CCF events have been in the instrumentation and control sub-system. However, the affected sub-component is different in all cases. Testing was the most common method of discovery and the proximate cause was evenly distributed among Internal to Component, Design/Construction/Installation/Manufacturer Inadequacy, and Operation/Human Error. The EDG is a complex machine and instrumentation and control is the most complex sub-system in the EDG. The instrumentation and control sub-system has the capability to shutdown or render inoperable the EDG component. The most recent Complete EDG CCF events have these characteristics.

EDG Complete CCF events mostly occur in the instrumentation and control sub-system and are discovered by testing. The attributes of proximate cause and coupling factor are random with respect to the completeness of the CCF event.

3.3 CCF Sub-System Overview

The EDGs are complex machines and can easily be thought of as a collection of sub-systems, each with many components. The EDG CCF data were reviewed to determine the affected sub-system and the affected sub-component in that sub-system. This was done to provide insights into what are the most vulnerable areas of the EDG component with respect to common-cause failure events. Section 2.4 describes these sub-systems.

Figure 3-5 shows the distribution of the CCF events by EDG sub-system. The highest number of events occurred in the instrumentation and control sub-system (41 events or 30 percent). The cooling, engine, fuel oil, and generator sub-systems are also significant contributors. Together, these five sub-systems comprise over 80 percent of the EDG CCF events. The battery, exhaust, and lubricating oil sub-systems are minor contributors. Section 4 of this report provides an in-depth analysis of the CCF events assigned to these sub-systems.

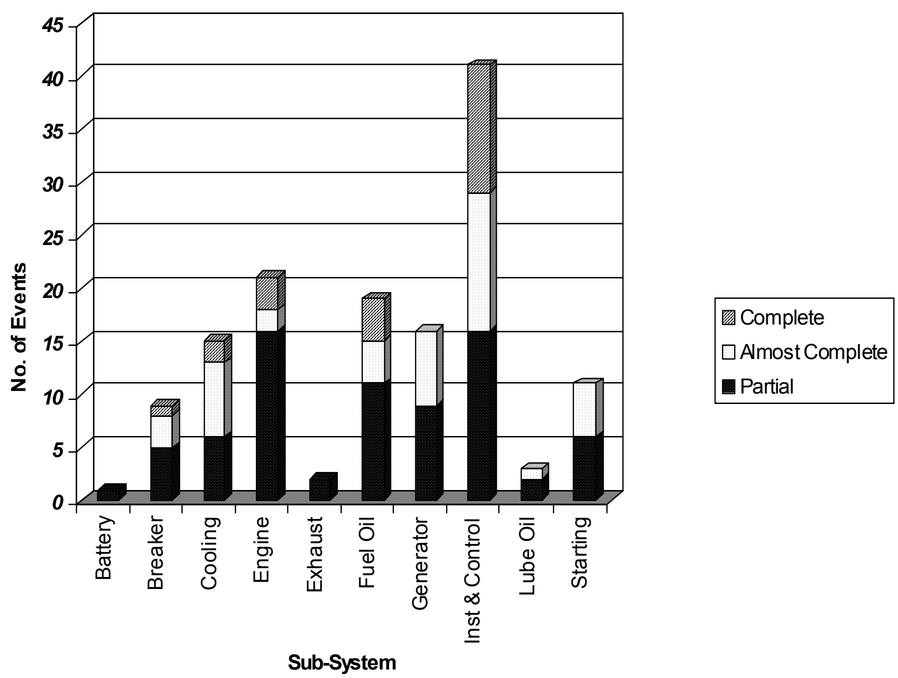

Figure 3-5. Sub-system distribution for all EDG CCF events.

3.4 CCF Proximate Cause

It is evident that each component fails because of its susceptibility to the conditions created by the root cause, and the role of the coupling factor is to make those conditions common to several components.

In analyzing failure events, the description of a failure in terms of the most obvious "cause" is often too simplistic. The sequence of events that constitute a particular failure mechanism is not necessarily simple. Many different paths by which this ultimate reason for failure could be reached exist. This chain can be characterized by two useful concepts— proximate cause and root cause.

A **proximate cause** of a failure event is the condition that is readily identifiable as leading to the failure. The proximate cause can be regarded as a symptom of the failure cause, and it does not in itself necessarily provide a full understanding of what led to that condition. As such, it may not be the most useful characterization of failure events for the purposes of identifying appropriate corrective actions.

The proximate cause classification consists of six major groups or classes:

- Design/Construction/Installation/Manufacture Inadequacy
- Operational/Human Error
- Internal to the component, including hardware-related causes and internal environmental causes
- External environmental causes
- Other causes
- Unknown causes.

The causal chain can be long and, without applying a criterion, identifying an event in the chain as a “root cause,” is often arbitrary. Identifying proximate causes in relation to the implementation of defenses is a useful alternative. The proximate cause is therefore the most basic reason or reasons for the component failure, which if corrected, would prevent recurrence. (See Table 4-2 in Section 4.1 for a display of the major proximate cause categories and a short description.) Reference 4 contains additional details on the proximate cause categories, and how CCF event proximate causes are classified.

Figure 3-6 shows the distribution of CCF events by proximate cause. The leading proximate cause was Design/Construction/Installation/Manufacture Inadequacy and accounted for about 33 percent of the total events. Internal to Component faults accounted for 30 percent of the total. Human error accounted for 22 percent of the total events. To a lesser degree, External Environment and the Other proximate cause categories were assigned to the EDG component.

Table A-1 in Appendix A presents the entire EDG data set sorted by the proximate cause. This table can be referred to when reading the following discussions to see individual events described.

The **Design/Construction/Installation/Manufacture Inadequacy** proximate cause group is the most likely for the EDGs and encompasses events related to the design, construction, installation, and manufacture of components, both before and after the plant is operational. Included in this category are events resulting from errors in equipment and system specifications, material specifications, and calculations. Events related to maintenance activities are not included.

Design/Construction/Installation/Manufacture Inadequacy errors resulted in 46 events. The failure mode for 28 of these events is fail-to-run, and the remaining 18 events have fail-to-start as the failure mode. There were six Complete CCF events in this proximate cause group: three Complete events were fail-to-run and three were fail-to-start. Five of the six Complete events were in the Instrumentation and control sub-system. One of these events was a Complete failure at one unit and the design flaw was detected at the other unit before failure. Except for this one event, the affected sub-component was different for each event.

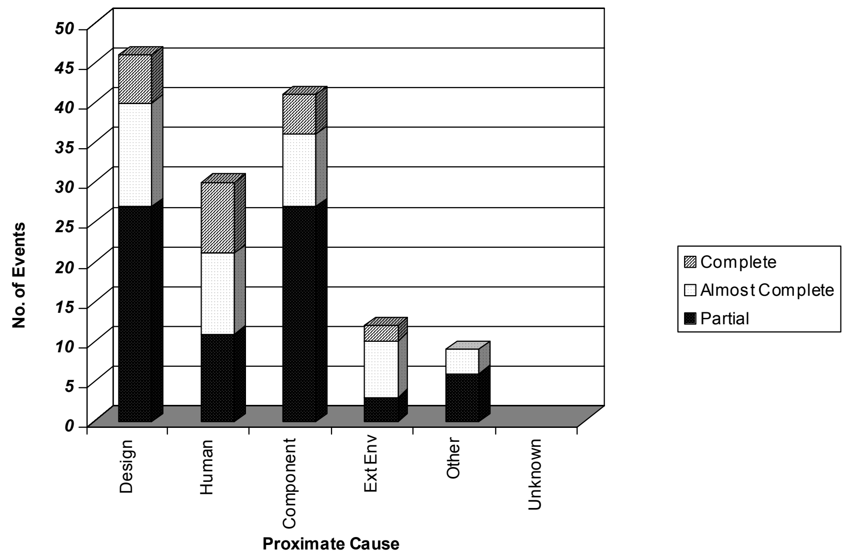

Figure 3-6. Proximate cause distribution for all EDG CCF events.

The **Internal to Component** proximate cause category is important for the EDGs and encompasses the malfunctioning of hardware internal to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms that are influenced by the ambient environment of the component. Specific mechanisms include erosion, corrosion, internal contamination, fatigue, wear-out, and end of life. Internal to Component errors resulted in 41 events. Of these, 20 were classified as fail-to-run and 21 were fail-to-start. There were five Complete failure events. The Engine and the Instrumentation and Control sub-systems each had two Complete events and the fifth Complete event was in the Cooling sub-system.

The **Operational/Human Error** proximate cause group is the next most likely for the EDG and represents causes related to errors of omission or commission on the part of plant staff or contractor staff. Included in this category are accidental actions, failures to follow the correct procedures or following inadequate procedures for construction, modification, operation, maintenance, calibration, and testing. This proximate cause group also includes deficient training. Operational/Human Error resulted in 30 EDG CCF events. These events included eight occurrences of accidental action, six occurrences of following the wrong procedure, and 16 occurrences due to use of inadequate procedures. The failure mode for 18 events is fail-to-run and 12 events have fail-to-start as the failure mode. There were nine Complete CCF events: seven were linked by maintenance and two were linked by system design. There are disproportionately more Complete events in this proximate cause category than in any other. This highlights the importance of maintenance and operations in the availability of the EDG component.

The **External Environment** proximate cause category represents causes related to a harsh environment that is not within the component design specifications. Specific mechanisms include chemical reactions, electromagnetic interference, fire or smoke, impact loads, moisture (sprays, floods, etc.), radiation, abnormally high or low temperature, vibration load, and acts of nature (high wind, snow, etc.). This proximate cause had 12 events assigned to it. The failure mode for eight events is fail-to-run, and four events have fail-to-start as the failure mode. There were two Complete CCF events, both resulting in fail-to-run. The two Complete events were due, in part, to engine vibration and were discovered by testing. This distribution of failure modes is not similar to the overall set of data, mostly because the environmental factors are more likely to affect the EDG during running time. For example, high temperature cooling water will not likely be too hot when the EDG starts, but after some amount of running time, due to the higher than average initial temperature, the cooling water temperature will increase above the acceptable limit.

The **Other** proximate cause group is comprised of events that indicated setpoint drift and the state of other components as the basic causes. Nine events were assigned to this category. The failure mode for five events is fail-to-run and four events have fail-to-start as the failure mode. There were no Complete CCF events in this category, and many of the events in this category are weak (i.e., small degradation values, weak coupling factors, and long time intervals among events).

3.5 CCF Coupling Factors

Closely connected to the proximate cause is the concept of **coupling factor**. A coupling factor is a characteristic of a component group or piece parts that links them together so that they are more susceptible to the same causal mechanisms of failure. Such factors include similarity in design, location, environment, mission, and operational, maintenance, design, manufacturer, and test procedures. These factors have also been referred to as examples of coupling mechanisms, but because they really identify a potential for common susceptibility, it is preferable to think of these factors as characteristics of a common-cause component group. Reference 4 contains additional detail about the coupling factors.

The coupling factor classification consists of five major classes:

- Hardware Quality based coupling factors,
- Design-based coupling factors,
- Maintenance coupling factors,
- Operational coupling factors, and
- Environmental coupling factors.

Figure 3-7 shows the coupling factor distribution for the events. Design is the leading coupling factor with 66 events (48 percent). Design coupling factors result from common characteristics among components determined at the design level. Maintenance with 39 events (28 percent) accounts for the majority of the remaining events. Maintenance also has a higher proportion of Complete events than any other coupling factor. Again, highlighting the importance of maintenance in the EDG CCFs. These two coupling factors account for the top 76 percent of the events.

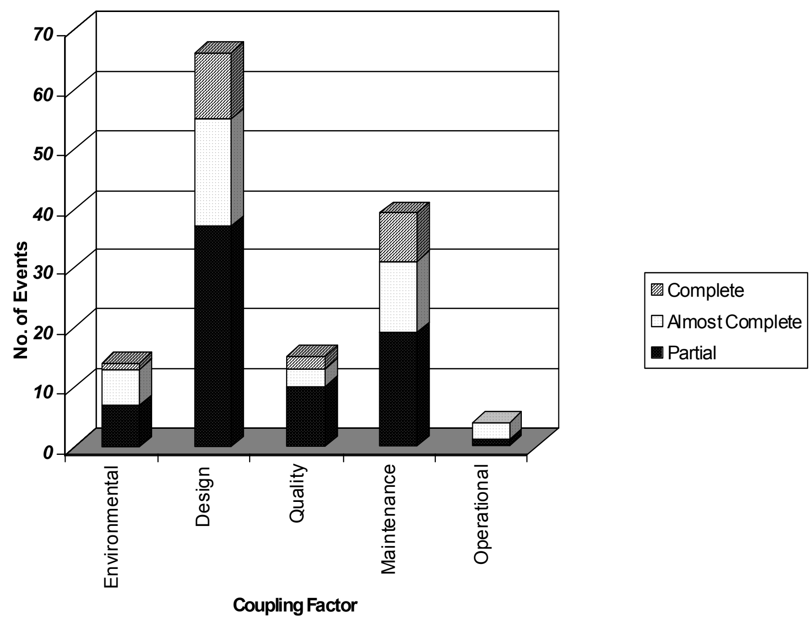

Figure 3-7. Coupling factor distribution for all EDG CCF events.

Table A-2 in Appendix A presents the entire EDG data set sorted by the coupling factor. This table can be referred to when reading the following discussions to see individual events described.

The design coupling factor is most prevalent in the Design/Construction/Installation/Manufacture Inadequacy proximate cause category. This means that the design was inadequate and was the link between the events. Examples of this follow:

- a single fault in a fire detection system caused all three EDGs to be unavailable,
- a modification was made to the load sequencers and the EDGs would not load during subsequent testing, and
- low lube-oil pressure sensors were replaced with modified sensors on all EDGs at both units and within 5 days all EDGs at both NPP units experienced failures due to a large calibration shift in the sensors.

The next most prevalent proximate cause under the Design coupling factor is Internal to Component. This means that the component failures, while not necessarily related to the original design, occurred in multiple components because all had the same design. Examples of these types of events are:

- damage to all lockout relays during an attempt to shutdown the EDGs resulting in the EDGs failing to restart,
- both EDGs failed due to failure of their electrical governor caused by a burnt resistor in the power supply of the control unit, and

- a service water valve to EDG coolers was mispositioned due to a faulty positioner, resulting in the EDGs overheating.

The **Maintenance** coupling factor indicates that the maintenance frequency, procedures, or personnel provided the linkage among the events. Operational/Human Error is the most prevalent proximate cause to be linked by maintenance. Examples of this are:

- misaligned breakers during an automatic start test,

- dirty contacts in the load sequencers, painted fuel rack pivot points, fuel oil isolated from EDGs,

- drained fuel oil day tanks,

- service water isolated to all EDGs during maintenance, and

- incorrect setpoints on a newly installed phase differential over-current relay in both EDGs.

The maintenance linkage to the component failure proximate cause usually indicated that more frequent maintenance could have prevented the CCF mechanism. Very few of these events actually resulted in Complete CCF events, but were detected as incipient failures. An example of this is timing devices, which failed due to aging, and were replaced. These devices had a history of an excessive need for calibration, yet were allowed to fail before being replaced. This event occurred in 1980 and since then, all CCFs in this category have been detected before complete failure.

The **Environment** based coupling factors propagate a failure mechanism via identical external or internal environmental characteristics. Examples of environmental based coupling factors are:

- degraded relay sockets caused by vibration and

- sticking limit switches caused by low temperatures.

Quality based coupling factors propagate a failure mechanism among several components due to manufacturing and installation faults. An example of a Quality based coupling factor is the failure of several RHR pumps because of the failure of identical pump air deflectors due to improper installation.

The **Operational** based coupling factors propagate a failure mechanism because of identical operational characteristics among several components. For example, failure of three redundant HHSI pumps to start because the breakers for all three pumps were racked-out because of operator error.

3.6 CCF Discovery Method Overview

An important facet of these CCF events is the way in which the failures were discovered. Each CCF event was reviewed and categorized into one of the four discovery categories: Test, Maintenance, Demand, or Inspection. These categories are defined as:

Test — The equipment failure was discovered either during the performance of a scheduled test or because of such a test. These tests are typically periodic surveillance tests, but may be any of the other tests performed at nuclear power plants, e.g., post-maintenance tests and special systems tests.

Maintenance	The equipment failure was discovered during maintenance activities. This typically occurs during preventative maintenance activities.
Demand	The equipment failure was discovered during an actual demand for the equipment. The demand can be in response to an automatic actuation of a safety system or during normal system operation.
Inspection	The equipment failure was discovered by personnel, typically during system tours or by operator observations.

Figure 3-8 shows the distribution of how the events were discovered or detected. Testing accounted for 90 events (65 percent), Inspection for 28 events (20 percent), 12 events (9 percent) were discovered during an actual Demand, and eight events (6 percent) were discovered during Maintenance activities. These results are as expected considering the extensive and frequent surveillance test requirements for EDGs contained in the Technical Specifications.

Table A-3 in Appendix A presents the entire EDG data set sorted by the discovery method. This table can be referred to when reading the following discussions to see individual events described.

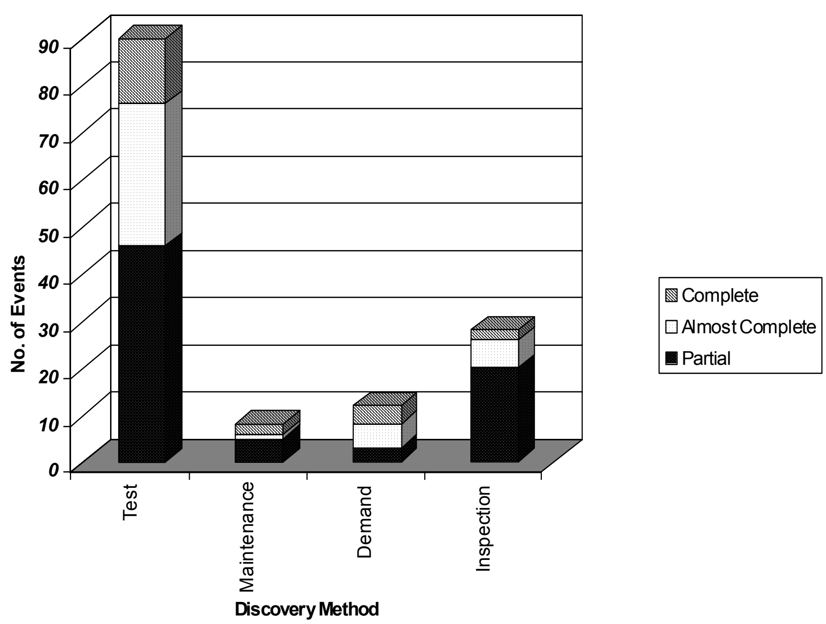

Figure 3-8. Discovery method distribution for all EDG CCF events.

3.7 Other EDG CCF Observations

Figure 3-9 shows the distribution of CCF events grouped by EDG manufacturers and graphically demonstrates the data in Table 3-2. EDG manufacturer data in Table 3-2 was taken from *Emergency Diesel Generator Power System Reliability 1987-1993*.[10] A statistical test was performed to determine whether the occurrence of CCF events was independent of the manufacturer. There is no evidence that the number of CCF events differs among manufacturers (p-value = 0.365).

Table 3-2. EDG manufacturer and CCF event distribution.

Manufacturer Name	Total EDGs Installed	Percent Installed	No. CCFs	Percent CCF
Other	1	0.4%	0	0.0%
Worthington Corp	4	1.7%	4	2.9%
Nordberg Mfg	8	3.4%	6	4.3%
Transamerica Delaval	22	9.3%	16	11.6%
ALCO Power	23	9.7%	18	13.0%
Cooper Bessemer	36	15.3%	23	16.7%
Fairbanks Morse/Colt	67	28.4%	28	20.3%
Electro Motive	75	31.8%	43	31.2%
Total	236	100.0%	138	100.0%

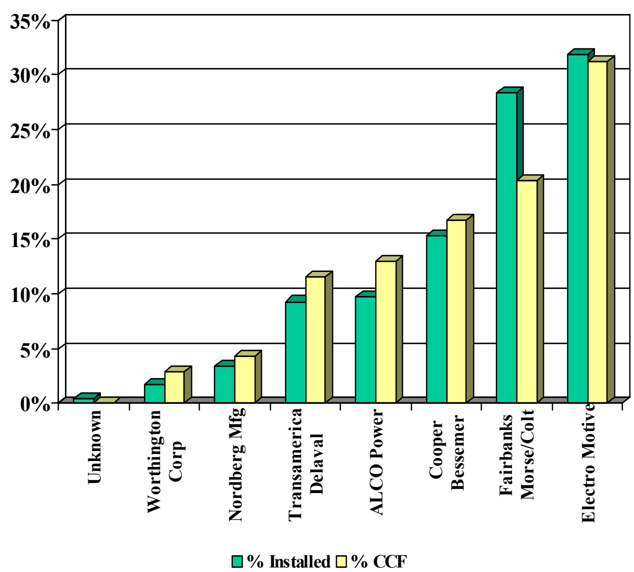

Figure 3-9. Comparison of EDG manufacturer population and occurrence of CCF events.

Figure 3-10 shows the distribution of EDG CCF events among the NPP units. The data are based on 109 NPP units represented in the insights CCF studies. Forty-two NPP units each had one CCF event during the period; 34 NPP units did not experience a CCF event. The zero and one CCF event counts account for about 70 percent of the NPP units. Seventeen percent of the NPP units have experienced three or more EDG CCF events. This may indicate that the majority of the NPP units have maintenance and testing programs to identify possible EDG CCF events and work towards preventing either the first event or any repeat events. Less than 6 percent of the NPP units have experienced four or more EDG CCF events.

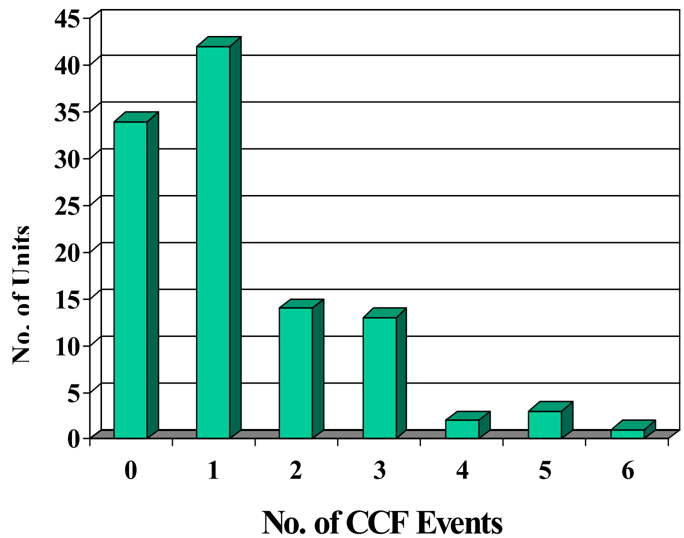

Figure 3-10. Distribution of NPP units experiencing a multiplicity of CCFs for all EDG CCF events.

4. ENGINEERING INSIGHTS BY EMERGENCY DIESEL GENERATOR SUB-SYSTEM

4.1 Introduction

This section presents an overview of the CCF data for the EDG component that have been collected from the NRC CCF database, grouped by the affected sub-system. The EDGs are complex machines and can easily be thought of as a collection of sub-systems, each with many components. The EDG CCF data were reviewed to determine the affected sub-system and the affected sub-component in that sub-system. This was done to provide insights into what are the most vulnerable areas of the EDG component with respect to common-cause failure events. For the descriptions of the EDG and its sub-systems, see Section 2.4.

Table 4-1 summarizes the CCF events by sub-system. Each discussion of an EDG sub-system summarizes selected attributes of that sub-system. A list of the EDG CCF Complete events follows; displaying the proximate cause, failure mode, and a short description of the event. For a listing of all EDG CCF events, see Appendix B.

Table 4-1. Summary of sub-systems.

Sub-System	Sub-Section	Partial	Almost Complete	Complete	Total	Percent
Inst. & Control	4.2	16	13	12	41	29.7%
Engine	4.3	16	2	3	21	15.2%
Fuel Oil	4.4	11	4	4	19	13.8%
Generator	4.5	9	7		16	11.6%
Cooling	4.6	6	7	2	15	10.9%
Starting Air	4.7	6	5		11	8.0%
Output Circuit Breaker	4.8	5	3	1	9	6.5%
Lube Oil	4.9	2	1		3	2.2%
Exhaust	4.10	2			2	1.4%
Battery	4.11	1			1	0.7%
Total		74	42	22	138	100.0%

The majority of the EDG CCF events originated in the instrumentation and control sub-system. The cooling, engine, fuel oil, and generator sub-systems each contribute significantly to the EDG CCF events. These five sub-systems contribute over 80 percent of the EDG CCF events.

In this study, the proximate causes of the EDG CCF events in the NRC CCF database have been grouped into higher-order proximate cause categories to facilitate the graphical depiction of proximate causes. Table 4-2 contains a hierarchical mapping of the proximate causes of EDG CCF events into the higher-order groups. Since the graph x-axis labels are restricted in length, the proximate cause category names have been shortened and are shown in parenthesis in Table 4-2. Table 4-2 also describes each of these groups.

Table 4-2. Proximate cause hierarchy.

PROXIMATE CAUSE
- Design/Const./Install./Manufacture (Design)
  - Design Error
  - Manufacturing Error
  - Installation/Construction Error
  - Design Modification Error
- Operational/Human Error (Human)
  - Accidental Action
  - Inadequate/Incorrect Procedure
  - Failure to Follow Procedure
  - Inadquate Training
  - Inadequate Maintenance
- External Environment (Ext Env)
  - Fire/Smoke
  - Humidity/Moisture
  - High/Low Temperature
  - Electromagnetic Field
  - Radiation
  - Bio-organisms
  - Contamination/Dust/Dirt
  - Acts of Nature
    - Wind
    - Flood
    - Lightning
    - Snow/Ice
- Internal to Component (Component)
- Other
  - State of Other Component
  - Setpoint Drift
- Unknown
	Design/Construction/Installation/Manufacture Inadequacy. This category encompasses actions and decisions taken during design, manufacture, or installation of components both before and after the plant is operational.
	
	Operational/Human Error (Plant Staff Error). Represents causes related to errors of omission and commission on the part of plant staff. An example is a failure to follow the correct procedure. This category includes accidental actions, and failure to follow procedures for construction, modification, operation, maintenance, calibration, and testing. It also includes ambiguity, incompleteness, or error in procedures for operation and maintenance of equipment. This includes inadequacy in construction, modification, administrative, operational, maintenance, test, and calibration procedures.
	
	External Environment. Represents causes related to a harsh external environment that is not within component design specifications. Specific mechanisms include electromagnetic interference, fire/ smoke, impact loads, moisture (sprays, floods, etc.), radiation, abnormally high or low temperature, and acts of nature.
	
	Internal to Component. Is associated with the malfunctioning of hardware internal to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms. It includes the influence of the internal environment of a component. Specific mechanisms include erosion/ corrosion, vibration, internal contamination, fatigue, and wearout/end of life.
	
	Other. Represents other causes including the State of Another Component; The component is functionally unavailable because of failure of a supporting component or system and Setpoint Drift; The component is functional, but will not perform its function within the required range due to a degraded piece-part.
	
	Unknown. This cause category is used when the cause of the component state cannot be identified.

4.2 Instrumentation and Control

Forty-one CCF events affected the instrumentation and control sub-system (see Table B-1 in Appendix B, items 84–124). Of these 41 events, 25 were fail-to-start and 16 were fail-to-run. Twelve instrumentation and control EDG CCF events were Complete CCF events. Table 4-3 contains a summary of these events by proximate cause group and degree of failure. Figure 4-1 shows that the most likely proximate cause groups are Design, Construction and Manufacture Inadequacies, Operational/Human Actions, and Internal to the Component.

Table 4-3. CCF events in instrumentation and control sub-system by cause group and degree of failure.

Proximate Cause Group	Complete	Almost Complete	Partial	Total	Percent
Design/Construction/Installation/ Manufacture Inadequacy	5	5	5	15	36.6%
Internal to Component	2	2	5	9	22.0%
Operational/Human	4	2	3	9	22.0%
External Environment	1	3	1	5	12.2%
Other		1	2	3	7.3%
Total	12	13	16	41	100.0%

The Design/Construction/Installation/Manufacture Inadequacy proximate cause group had 15 events (37 percent) of which five were Complete and five were Almost Complete (see Table B-1 in Appendix B, items 84–98). Affected sub-components included fuses, load sequencers, relays, and sensors. The main causes for this group included installing the wrong equipment, not installing the equipment correctly, and poor design of equipment. This combination of the instrumentation and control sub-system and the Design/ Construction/Installation/Manufacture Inadequacy proximate cause is the most likely to contribute to a CCF of the EDG component. Many of these events are the result of modifications or repairs made to an existing installed EDG. The review of modifications and careful inspection of redesigned or replacement parts are the most important defenses against this kind of CCF.

The Internal to Component proximate cause group had nine events (22 percent) of which two were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 104–112). Affected sub-components included limit switches, and relays. The causes included foreign material in the air control system, malfunctioning equipment, dirty piece-parts, and damaged equipment.

The Operational/Human Error proximate cause group contains nine events (22 percent) of which four were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 113–121). Affected sub-components included relays and the load sequencers. The causes of these events included errors made during maintenance of equipment, poor maintenance, performing testing incorrectly, and inattentive operators. This proximate cause group has the highest observed fraction of Complete CCF events in the instrumentation and control sub-system. It is the combination of the susceptibility of the instrumentation and control sub-system to small errors and the ability of the human element to fail multiple components in a group that led to this result.

The External Environment proximate cause group contains five events (12 percent) of which one was Complete and three were Almost Complete (see Table B-1 in Appendix B, items 99–103). Affected sub-components included the governor and miscellaneous sensors. The main causes in this group are long term heat fatigue of resistors, vibration, and cold outside temperature.

The Other proximate cause group contains three events (7 percent) of which none were Complete and one was Almost Complete (see Table B-1 in Appendix B, items 122–124).

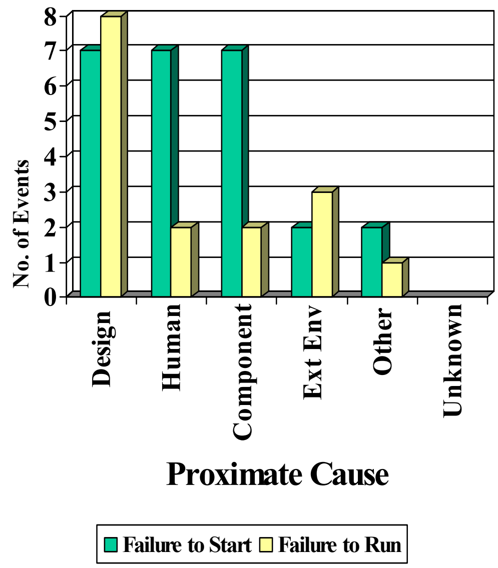

Figure 4-1. Distribution of proximate causes for the instrumentation and control sub-system.

Testing was the most likely method of discovery for instrumentation and control EDG events (25 out of the 41 events, 61 percent) as shown in Figure 4-2. The EDGs are frequently tested and not normally run to supply power. This tends to make testing the most likely method of discovery. Inspection and Demand make up the next most likely discovery methods. Maintenance is the least likely discovery method. The most likely sub-components involved in CCF events were the relays and governor as shown in Figure 4-3.

Table 4-4 lists the short descriptions by proximate cause for the Complete events, the events that failed all the EDGs. The descriptions of all EDG CCF events can be found in Appendix B.

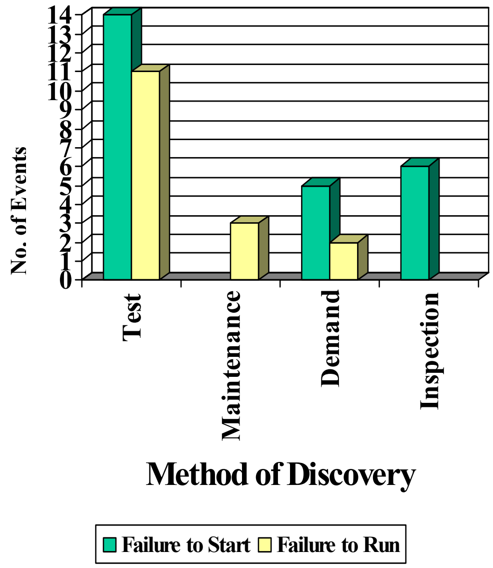

Figure 4-2. Distribution of the method of discovery for the instrumentation and control sub-system.

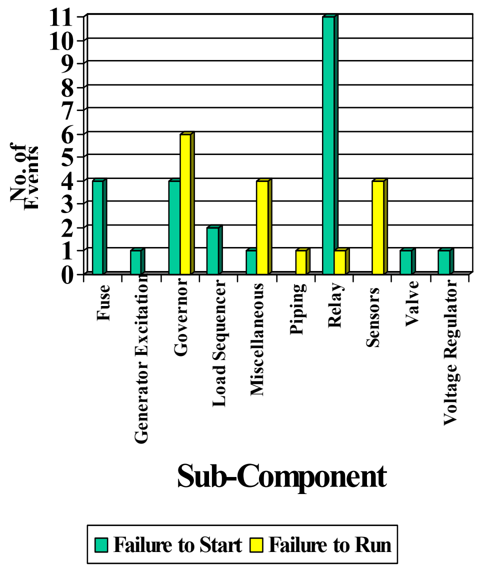

Figure 4-3. Distribution of the affected sub-component for the instrumentation and control sub-system.

Table 4-4. Instrumentation and control sub-system event short descriptions for Complete events.

Proximate Cause Group	Failure Mode	Description
Design/ Construction/ Manufacture/ Installation Inadequacy	Failure to Run	Breakers tripped on over-current. Incorrect bulb-type indication was installed in the local panel.
Design/ Construction/ Manufacture/ Installation Inadequacy	Failure to Start	A simulated CO2 actuation blew the fuse in the EDG control panel. The condition resulted from a design deficiency during installation of the CO2 system.
Design/ Construction/ Manufacture/ Installation Inadequacy	Failure to Run	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
Design/ Construction/ Manufacture/ Installation Inadequacy	Failure to Start	Diesel sequencers did not load during test. The cause was inadequate design understanding and inadequate post-modification testing.
Design/ Construction/ Manufacture/ Installation Inadequacy	Failure to Start	Relay trips were caused by failed zener diodes in surge protection, which had been installed backwards. The relays were replaced with relays without zener diodes.
External Environment	Failure to Run	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
Internal to Component	Failure to Start	During the performance of a pre-operational test, the safety injection signal to the EDGs was picked up. Both EDGs at one unit did not start.
Internal to Component	Failure to Start	During attempts to shutdown the EDGs, the lockout relays were damaged, thereby making the EDGs inoperable.
Operational/ Human Error	Failure to Start	All EDGs started on an inadvertent SIAS (technician error) during testing. The licensed operator stopped the EDGs prior to the SIAS reset, causing EDGs to be inoperable.
Operational/ Human Error	Failure to Run	One EDG stopped during a test run due to an incorrect setpoint on a newly installed phase differential overcurrent relay. Both EDGs had the same setpoint.
Operational/ Human Error	Failure to Start	Shutdown sequencers to both EDGs failed during testing. One EDG failed due to dirty contacts. The other EDG failed due to a sticking clutch. Both failures were attributed to maintenance and test equipment.
Operational/ Human Error	Failure to Start	During surveillance testing, the operator mistakenly caused a blackout signal, causing all EDGs to start. EDGs were stopped, but during restoration process, all were inoperable for approximately 10 minutes.

4.3 Engine

Twenty-one EDG CCF events affected the engine sub-system, of which three events are Complete events (see Table B-1 in Appendix B, items 26–46). Three events were fail-to-start and eighteen events were fail-to-run. The most likely proximate causes are Design/Construction/Installation/ Manufacture Inadequacy, and Internal to Component, resulting in fail-to-run is shown in Figure 4-4. Table 4-5 contains a summary of these events by proximate cause group and failure.

Table 4-5. CCF events in engine sub-system by cause group and degree of failure.

Proximate Cause Group	Complete	Almost Complete	Partial	Total	Percent
Design/Construction/Installation/ Manufacture Inadequacy	1		9	10	47.6%
Internal to Component	2	2	4	8	38.1%
Operational/Human			3	3	14.3%
External Environment				0	0.0%
Other				0	0.0%
Total	3	2	16	21	100.0%

The Design/Construction/Installation/Manufacture Inadequacy proximate cause group had 10 events (48 percent) of which one was Complete and none were Almost Complete (see Table B-1 in Appendix B, items 26–35). Affected sub-components included the turbocharger and the shaft. The main causes for this group involved inadequate design for the intended service, underrated EDGs, and manufacturing defects.

The Internal to Component proximate cause group had eight events (38 percent) of which two were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 36–43). Affected sub-components included the fuel rack, sensors, exhaust valve, governor, and piston. The causes included vibration-induced failure, inadequate lubrication, and early failure of piece-parts. This proximate cause group has the highest fraction of Complete events for the engine sub-system.

The Operational/Human Error proximate cause group contains three events (14 percent) of which none were Complete and none were Almost Complete (see Table B-1 in Appendix B, items 44–46). Affected sub-components included pistons and bearings. The causes of these events included errors made during maintenance of equipment, poor maintenance, and inadequate procedures.

Testing was the most likely method of discovery for engine EDG events (12 out of the 21 events, 57 percent) as shown in Figure 4-5. The EDGs are frequently tested and not normally run to supply power. This would tend to make testing the most likely method of discovery. Inspection makes up the next most likely discovery method. Maintenance and demand are unlikely discovery methods. The most likely sub-components involved in CCF events were the fuel racks, pistons, and turbochargers as shown in Figure 4-6.

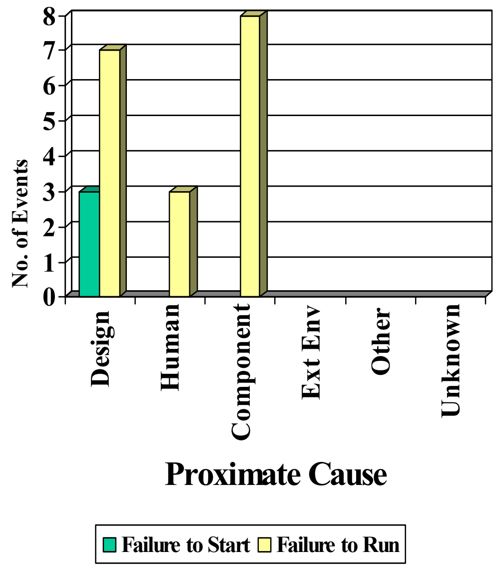

Figure 4-4. Distribution of proximate causes for the engine sub-system.

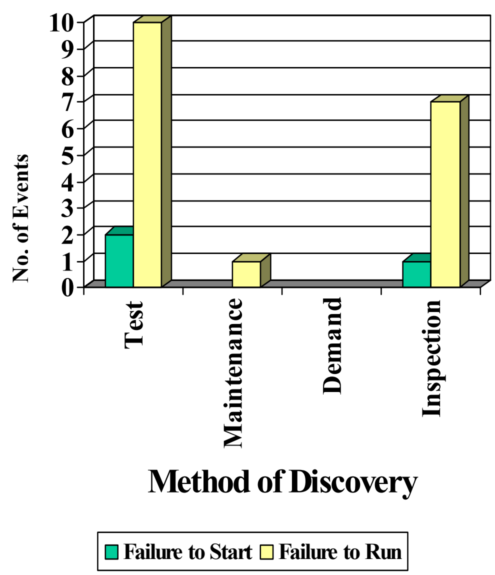

Figure 4-5. Distribution of the method of discovery for the engine sub-system.

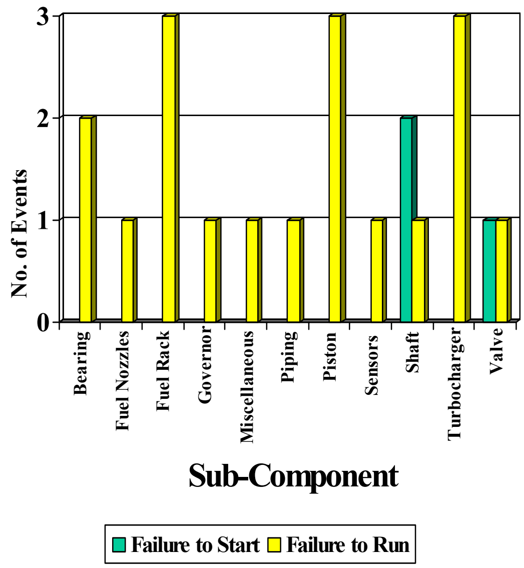

Figure 4-6. Distribution of the affected sub-component for the engine sub-system.

Table 4-6 lists the short descriptions by proximate cause for the Complete events, the events that failed all the EDGs. The descriptions of all EDG CCF events can be found in Appendix B.

Table 4-6. Engine sub-system event short descriptions for Complete events.

Proximate Cause Group	Failure Mode	Description
Design/ Construction/ Manufacture/ Installation Inadequacy	Failure to Run	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
Internal to Component	Failure to Run	Failure of the electrical governors was caused by a burnt resistor in the power supply of the control units.
Internal to Component	Failure to Run	EDG trips occurred due to an out of calibration temperature switch, leaking air start valve gasket, clearing of lube oil strainer, cleaning of air ejector, problem with air start distributor, out of calibration pressure switch and shattered/leaking piston.

4.4 Fuel Oil

Nineteen events were attributed to the fuel oil sub-system of the EDGs, four of which were Complete events (see Table B-1 in Appendix B, items 49–67). The most likely proximate cause is Operational/Human Error resulting in fail-to-run as shown in Figure 4-7. Table 4-7 contains a summary of these events by proximate cause group and failure.

There were four Complete failures, three of which were caused by a failure to follow procedure. Two of these were valve lineup problems. The other was due to a design flaw. Plugging of the fuel oil filters is another significant aspect of this sub-system. The external dependency of this sub-system helped spread the contaminated fuel oil to both NPP units at a site.

Table 4-7. CCF events in the fuel oil sub-system by cause group and degree of failure.

Proximate Cause Group	Complete	Almost Complete	Partial	Total	Percent
Design/Construction/Installation/ Manufacture Inadequacy		1	2	3	15.8%
Internal to Component		1	5	6	31.6%
Operational/Human	3	2	4	9	47.4%
External Environment	1			1	5.3%
Other				0	0.0%
Total	4	4	11	19	100.0%

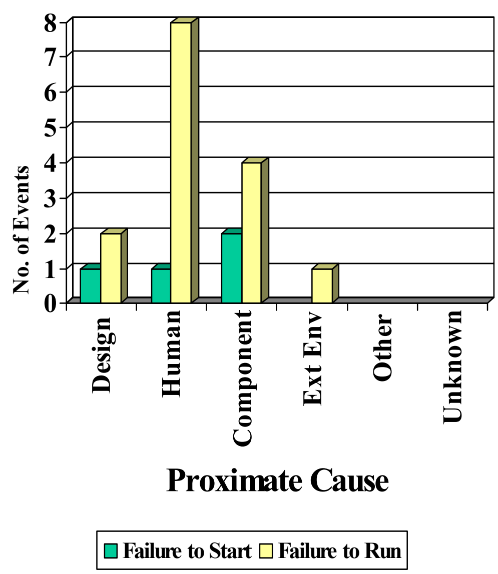

Figure 4-7. Distribution of proximate causes for the fuel oil sub-system.

The Operational/Human Error proximate cause group contains nine events (47 percent) of which three were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 59–67). Affected sub-components included the pumps, various valves, the fuel rack, strainers, and piping. The causes of these events included poor maintenance, operator inattention, and errors made during maintenance of equipment.

The Internal to Component proximate cause group had six events (32 percent) of which none were Complete and one was Almost Complete (see Table B-1 in Appendix B, items 53–58). Affected sub-components included the fuel oil strainers, pumps, and gaskets. The causes were from fungus growth and aging.

The Design/Construction/Installation/Manufacture Inadequacy proximate cause group had three events (16 percent) of which none were Complete and one was Almost Complete (see Table B-1 in Appendix B, items 49–51). Affected sub-components included the fuel oil pump and the tank level indication. Inadequate design of pump parts led to leakage and the tank level indication was erroneous.

The External Environment proximate cause group contains one event (5 percent), which was Complete (see Table B-1 in Appendix B, item 52). This event caused a leak to be developed in the piping due to vibration.

Testing was the most likely method of discovery for fuel oil EDG events (13 out of the 19 events, 68 percent) as shown in Figure 4-8. The EDGs are frequently tested and not normally run to supply power. This would tend to make testing the most likely method of discovery. Inspection and Demand make up the next most likely discovery methods. Maintenance is the least likely discovery method. The most likely sub-components involved in CCF events were the pumps as shown in Figure 4-9.

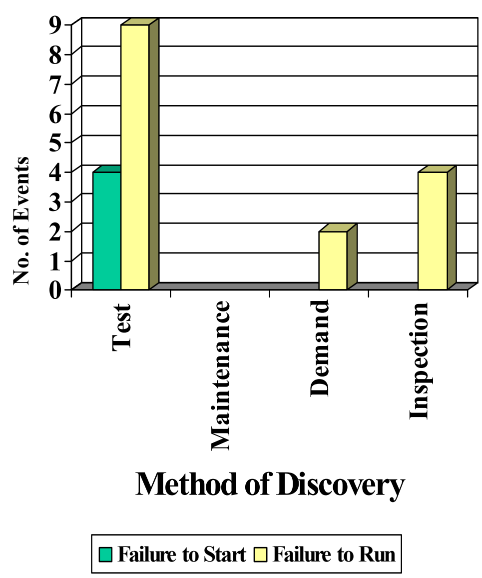

Figure 4-8. Distribution of the method of discovery for the fuel oil sub-system.

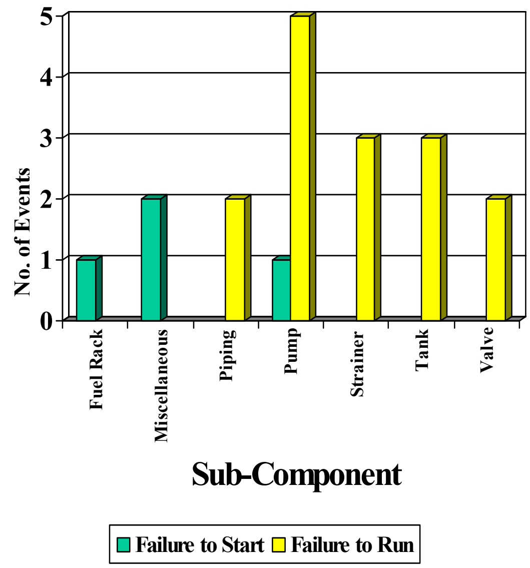

Figure 4-9. Distribution of the affected sub-component for the fuel oil sub-system.

Table 4-8 lists the short descriptions by proximate cause for the Complete events, the events that failed all the EDGs. The descriptions of all EDG CCF events can be found in Appendix B.

Table 4-8. Fuel oil sub-system event short descriptions for Complete events.

Proximate Cause Group	Failure Mode	Description
Operational/ Human Error	Failure to Run	An operator drained all fuel oil day tanks while sampling the fuel oil.
External Environment	Failure to Run	EDG fuel supply hose developed a leak due to excessive localized flexure and vibration. Following repair, EDG tripped due to low control air pressure caused by fitting loosened by engine vibration. Another EDG fuel injector supply line failed due to metal fatigue and vibration.
Operational/ Human Error	Failure to Run	Both fuel oil valves were closed during transfers of fuel, isolating the normal supply from the respective fuel transfer pumps to each of the day tanks.
Operational/ Human Error	Failure to Start	Fuel rack binding of the fuel rack pivot points was caused by paint, which occurred during painting of the EDGs. The same problem was found on the other EDG, which had been painted at the same time.

4.5 Generator

Sixteen events were attributed to the generator sub-system of the EDGs, none of which were Complete events (see Table B-1 in Appendix B, items 68–83). The most likely proximate cause is Design/Construction/Installation/Manufacture Inadequacy affecting both fail-to-start and fail-to-run as shown in Figure 4-10. Table 4-9 contains a summary of these events by proximate cause group and failure.

Table 4-9. CCF events in the generator sub-system by cause group and degree of failure.

Proximate Cause Group	Complete	Almost Complete	Partial	Total	Percent
Design/Construction/Installation/ Manufacture Inadequacy		3	4	7	43.8%
Internal to Component			3	3	18.8%
Operational/Human		1		1	6.3%
External Environment		1		1	6.3%
Other		2	2	4	25.0%
Total	0	7	9	16	100.0%

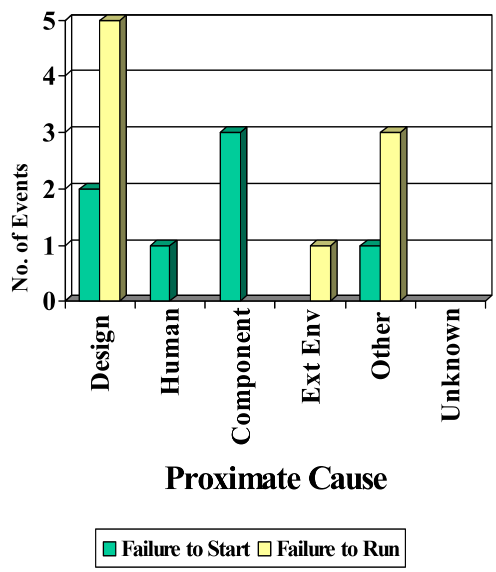

Figure 4-10. Distribution of proximate causes for the generator sub-system.

The Design/Construction/Installation/Manufacture Inadequacy proximate cause group had seven events (44 percent) of which none were Complete and three were Almost Complete (see Table B-1 in Appendix B, items 68–74). Affected sub-components included relays, voltage regulators, rotors, and generator excitation. The main causes for this group involved design faults, material incompatibility, drawing inaccuracies, incorrect material, and inadequate cooling design.

The Other proximate cause group contains four events (25 percent) of which none were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 80–83). The main causes in this group are load changes, room cooling, and load sequencer relays.

The Internal to Component proximate cause group had three events (19 percent) of which none were Complete and none were Almost Complete (see Table B-1 in Appendix B, items 76–78). The three events occurred at all three units of a utility. Affected sub-components were the power resistors. The power resistors were defective.

The Operational/Human Error proximate cause group contains one Almost Complete event (6 percent) (see Table B-1 in Appendix B, item 79). The operator tripped the EDG.

The External Environment proximate cause group contains one Almost Complete event (6 percent) (see Table B-1 in Appendix B, item 75). A short was caused by inadequate cooling.

Testing was the most likely method of discovery for generator EDG events (13 out of the 16 events, 81 percent) as shown in Figure 4-11. The EDGs are frequently tested and not normally run to supply power. This would tend to make testing the most likely method of discovery. Inspection, Demand, and Maintenance make up the least likely discovery methods. The most likely sub-components involved in CCF events were the voltage regulators and power resistors as shown in Figure 4-12.

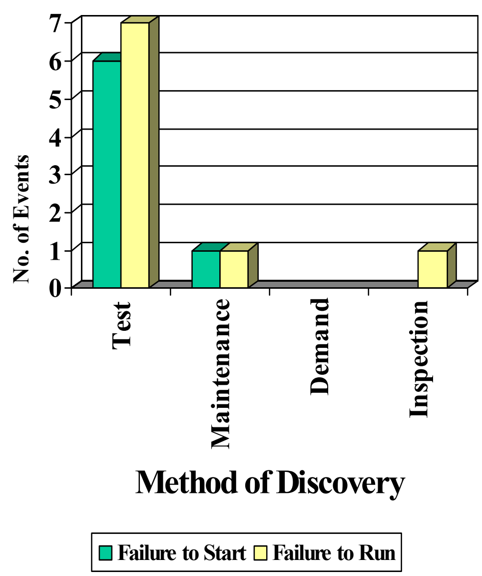

Figure 4-11. Distribution of the method of discovery for the generator sub-system.

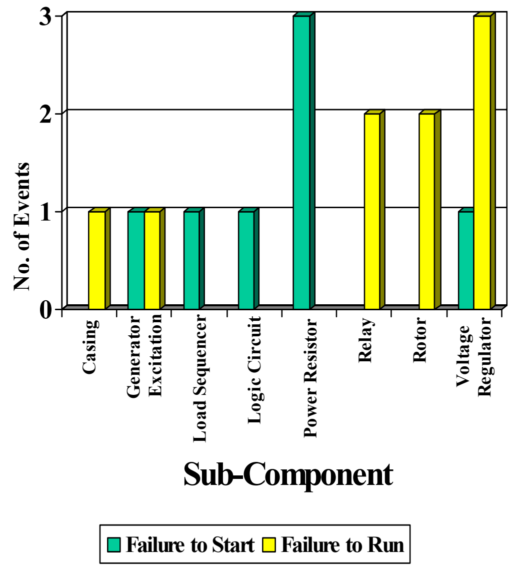

Figure 4-12. Distribution of the affected sub-component for the generator sub-system.

4.6 Cooling

Fifteen events were attributed to the cooling sub-system of the EDGs, of which two events are Complete events (see Table B-1 in Appendix B, items 11–25). The most likely proximate cause is Design/Construction/Installation/Manufacture Inadequacy affecting the fail-to-run as shown in Figure 4-13. Table 4-10 contains a summary of these events by proximate cause group and failure.

Table 4-10. CCF events in the cooling sub-system by cause group and degree of failure.

Proximate Cause Group	Complete	Almost Complete	Partial	Total	Percent
Design/Construction/Installation/ Manufacture Inadequacy		2	3	5	33.3%
Internal to Component	1	1	1	3	20.0%
Operational/Human	1	2	1	4	26.7%
External Environment		2	1	3	20.0%
Other				0	0.0%
Total	2	7	6	15	100.0%

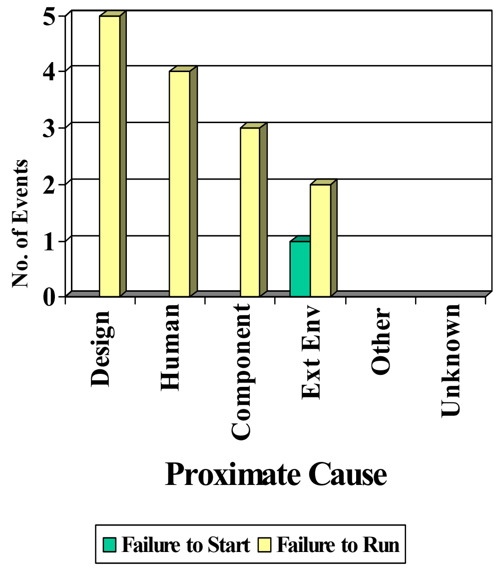

Figure 4-13. Distribution of proximate causes for the cooling sub-system.

The Design/Construction/Installation/Manufacture Inadequacy proximate cause group had five events (33 percent) of which none were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 11–15). Affected sub-components included piping, pumps, valves, and miscellaneous equipment. The main cause for this group was design errors.

The Operational/Human Error proximate cause group contains four events (27 percent) of which one was Complete and two were Almost Complete (see Table B-1 in Appendix B, items 22–25). The causes of these events included errors made during maintenance of equipment, poor maintenance, incorrect procedures, and inadequate control of biologic growth.

The Internal to Component proximate cause group had three events (20 percent) of which one was Complete and one was Almost Complete (see Table B-1 in Appendix B, items 19–21). The affected sub-components were valves and heat exchangers. The causes were faulty equipment and fouling.

The External Environment proximate cause group contains three events (20 percent) of which none were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 17–18). The main causes in this group are vibration fatigue, foreign material plugging the heat exchangers, and cold outside temperature.

Testing was the most likely method of discovery for cooling EDG events (10 out of the 15 events, 67 percent) as shown in Figure 4-14. The EDGs are frequently tested and not normally run to supply power. This would tend to make testing the most likely method of discovery. Inspection, Demand, and Maintenance make up the least likely discovery methods. The most likely sub-components involved in CCF events were the valves and heat exchangers as shown in Figure 4-15.

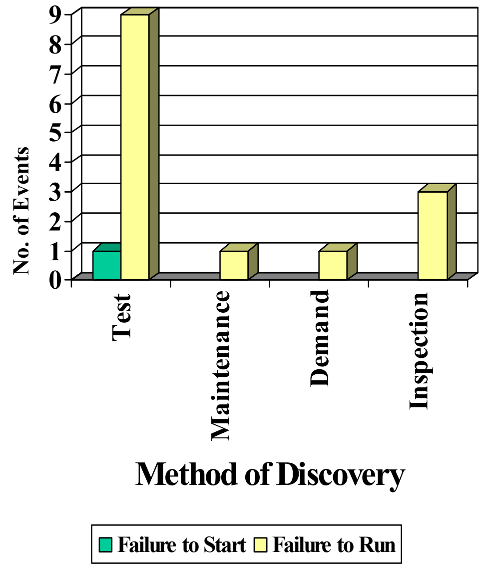

Figure 4-14. Distribution of the method of discovery for the cooling sub-system.

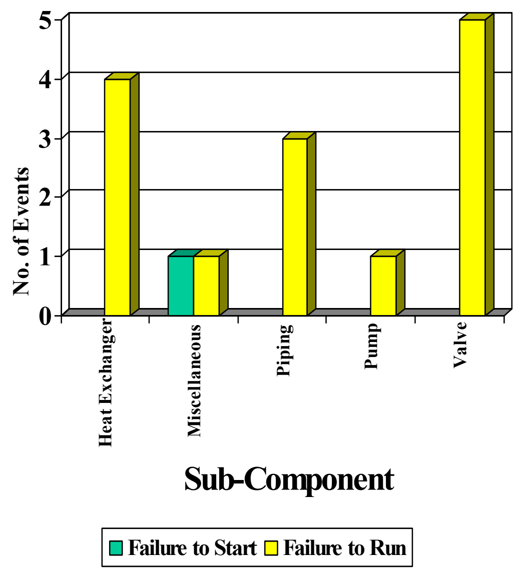

Figure 4-15. Distribution of the affected sub-component for the cooling sub-system.

Table 4-11 lists the short descriptions by proximate cause for the Complete events, the events that failed all the EDGs. The descriptions of all EDG CCF events can be found in Appendix B.

Table 4-11. Cooling sub-system event short descriptions for Complete events.

Proximate Cause Group	Failure Mode	Description
Operational/ Human Error	Failure to Run	Incorrect installation of pilot solenoid valves was caused by a lack of procedural adherence due to personnel error. Contributing causes were procedural inadequacies, inattention to detail, and inadequate skills.
Internal to Component	Failure to Run	Faulty positioners on service water valves in the cooling sub-system led to a failure of all EDGs.

4.7 Starting Air

Eleven events were attributed to the starting air sub-system of the EDGs, none being Complete events (see Table B-1 in Appendix B, items 128–138). The most likely proximate cause is the Internal to Component, resulting in fail-to-start as shown in Figure 4-16. Table 4-12 contains a summary of these events by proximate cause group and failure.

Table 4-12. CCF events in the starting air sub-system by cause group and degree of failure.

Proximate Cause Group	Complete	Almost Complete	Partial	Total	Percent
Design/Construction/Installation/ Manufacture Inadequacy		1	3	4	36.4%
Internal to Component		2	3	5	45.5%
Operational/Human		1		1	9.1%
External Environment		1		1	9.1%
Other				0	0.0%
Total	0	5	6	11	100.0%

The Internal to Component proximate group had five events (45 percent) of which none were Complete and two were Almost Complete (see Table B-1 in Appendix B, items 133–137). Affected sub-components included the air start motor, valves, strainers, and miscellaneous piece-parts. The causes were foreign material in the air system, corrosion, malfunctioning equipment, dirty piece-parts, and damaged equipment.

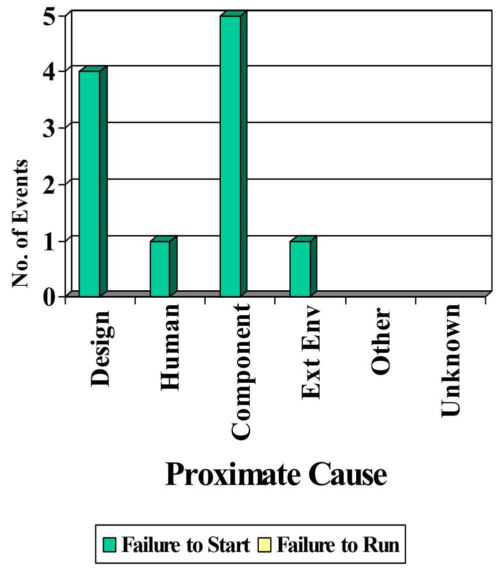

Figure 4-16. Distribution of proximate causes for the starting air sub-system.

The Design/Construction/Installation/Manufacture Inadequacy proximate cause group had four events (36 percent) of which none were Complete and one was Almost Complete (see Table B-1 in Appendix B, items 128–131). Affected sub-components included valves and solenoids. The main causes for this group involved inadequate manufacturing tolerances and incorrect component.

The Operational/Human Error proximate cause group contains one Almost Complete event (9 percent) (see Table B-1 in Appendix B, item 138). The air start motor was started while the EDG was running per a test procedure.

The External Environment proximate cause group contains one Almost Complete event (9 percent) (see Table B-1 in Appendix B, item 132). The air start valves were inoperable due to accelerated degradation.

Testing was the most likely method of discovery for starting air EDG events (10 out of the 11 events, 91 percent) as shown in Figure 4-17. The EDGs are frequently tested and not normally run to supply power. This would tend to make testing the most likely method of discovery. Inspection, Demand, and Maintenance make up the least likely discovery methods. The most likely sub-components involved in CCF events were the air-start valves and motor as shown in Figure 4-18.

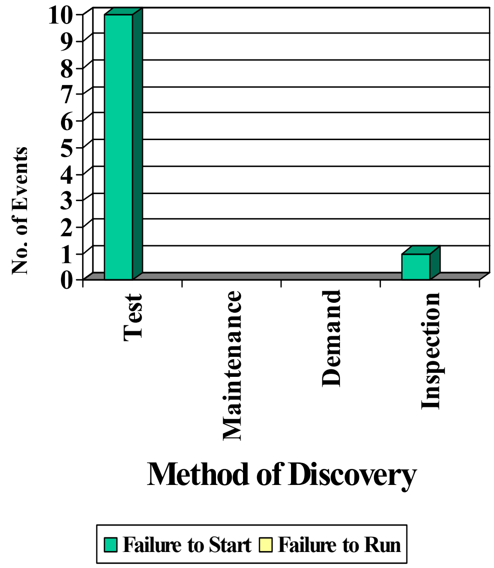

Figure 4-17. Distribution of the method of discovery for the starting air sub-system.

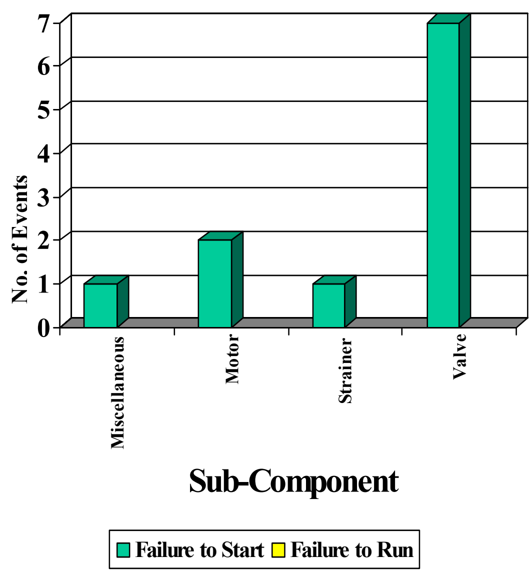

Figure 4-18. Distribution of the affected sub-component for the starting air sub-system.

4.8 Output Circuit Breaker

Nine events took place in the output circuit breaker sub-system of the EDGs, of which one was a Complete CCF event (see Table B-1 in Appendix B, items 2–10). The most likely proximate cause is Internal to Component affecting the fail-to-start as shown in Figure 4-19. Table 4-13 contains a summary of these events by proximate cause group and failure.

Table 4-13. CCF events in the output breaker sub-system by cause group and degree of failure.

Proximate Cause Group	Complete	Almost Complete	Partial	Total	Percent
Design/Construction/Installation/ Manufacture Inadequacy		1		1	11.1%
Internal to Component		1	5	6	66.7%
Operational/Human	1	1		2	22.2%
External Environment				0	0.0%
Other				0	0.0%
Total	1	3	5	9	100.0%

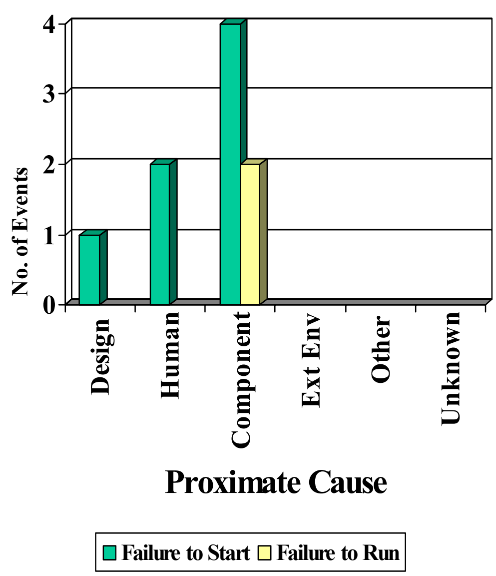

Figure 4-19. Distribution of proximate causes for the output circuit breaker sub-system.

Internal to Component was the most likely proximate cause group with six events (67 percent) of which none were Complete and one was Almost Complete (see Table B-1 in Appendix B, items 3–8).

Affected sub-components included relays, switches, and logic circuits. The causes included malfunctioning equipment, dirty piece-parts, and damaged equipment. Various breaker internal component failures are the most likely failures in this sub-system. However, the component failures are unlikely to cause a Complete CCF of the EDGs.

The Operational/Human Error proximate cause group contains two events (22 percent) (see Table B-1 in Appendix B, items 9–10). The Complete CCF event was caused by human error and this disabled all five EDGs at one unit. The Almost Complete event occurred when the operator incorrectly reset the lockout relays.

The Design/Construction/Installation/Manufacture Inadequacy proximate cause group had one Almost Complete event (11 percent) (see Table B-1 in Appendix B, item 2). Breaker switch contacts were faulty and the logic circuit was incorrect.

Testing was the most likely method of discovery for circuit breaker EDG events (4 out of the 9 events, 44 percent) as shown in Figure 4-20. The EDGs are frequently tested and not normally run to supply power. This would tend to make testing the most likely method of discovery. Inspection and Demand make up the next most likely discovery methods. Maintenance is the least likely discovery method. The most likely sub-components involved in CCF events were the relays and switches as shown in Figure 4-21.

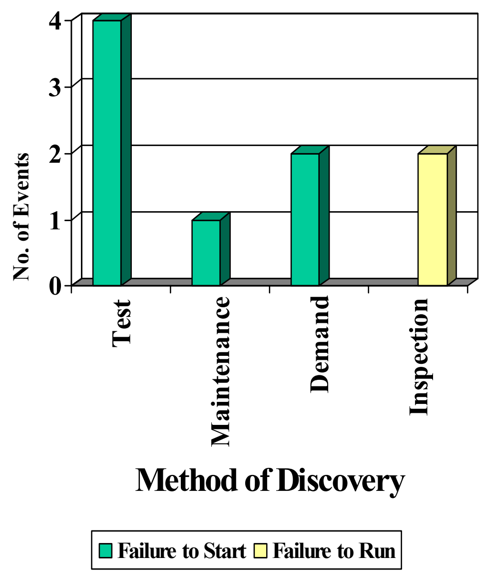

Figure 4-20. Distribution of the method of discovery for the output circuit breaker sub-system.

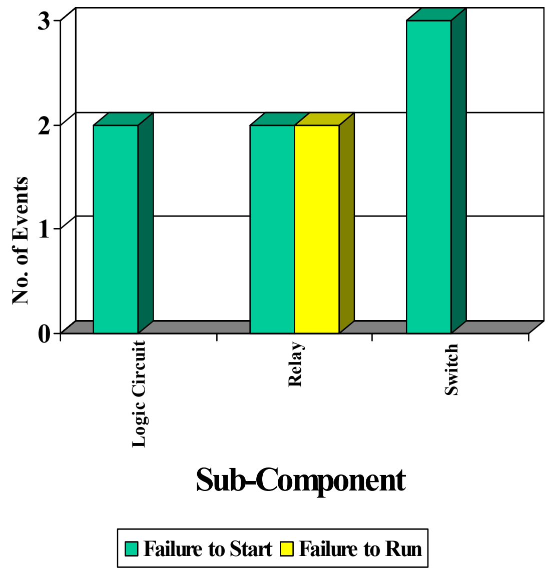

Figure 4-21. Distribution of the affected sub-component for the output circuit breaker sub-system.

Table 4-14 lists the short descriptions by proximate cause for the Complete events, the events that failed all the EDGs. The descriptions of all EDG CCF events can be found in Appendix B.

Table 4-14. Output circuit breaker sub-system event short descriptions for Complete events.

Proximate Cause Group	Failure Mode	Description
Operational/ Human Error	Failure to Start	All of the EDGs at one unit did not automatically start due to a misalignment during breaker line-up. The wrong DC knife switches were opened, thereby failing the EDG start relays.

4.9 Lube Oil

Three events were identified in the lube oil sub-system of the EDGs (see Table B-1 in Appendix B, items 125–127). No figures are shown since so few events affect this sub-system and none of the events were Complete. In one event, lube oil was degraded by the immersion heaters being left on by procedure, another event was due to a heat exchanger leak, and in the last event the lube-oil check valves leaked past their seats.

4.10 Exhaust

Two events were attributed to the exhaust sub-system of the EDGs (see Table B-1 in Appendix B, items 47–48). Neither of which was a Complete event. No figures are shown for this sub-system because of the low number of events. One event was due to water in the instrument air system affecting the exhaust damper and the other event was a manufacturing error of the exhaust damper rolling pins.

4.11 Battery

One event was identified in the battery sub-system (see Table B-1 in Appendix B, item 1). No figures are shown since so few events affect this sub-system. The EDG batteries had low specific gravity.

5. INSIGHTS FROM EDG FOREIGN EXPERIENCE

5.1 International Common-cause Data Exchange Project

Several member countries of Organization for Economic Cooperation and Development/Nuclear Energy Agency (OECD/NEA) established the International Common-cause Data Exchange (ICDE) Project to encourage multilateral co-operation in the collection and analysis of data relating to CCF events. The ICDE project operates under the umbrella of the OECD/NEA whose representative for this purpose is the Secretariat for Principal Working Group on Operating Reactor Experience. The ICDE project member countries and their sponsoring organizations are Canada, Finland, France, Germany, Spain, Switzerland, United Kingdom, and the United States.

5.2 Scope of the EDG Event Collection

Organizations from Finland, France, Germany, Sweden, Switzerland, United Kingdom, and the United States contributed data to the EDG data exchange. Results of the study are documented in the ICDE EDG project report.[10] A total of 106 CCF events were reported from nuclear power plants (pressurized water reactor, boiling water reactor, Magnux, and advanced gas-cooled reactor). The collection period varied from country to country but covered at least five years. The total time spans a period from 1982 through 1997. Thus, data are not necessarily complete for each country. The USA provided data from 1990 through 1995. Table 5-1 summarizes, by failure mode, the ICDE EDG CCF events collected and summarized in the ICDE EDG Insights study.

Table 5-1. Summary statistics of ICDE emergency diesel generator data.

		Degree of Failure Observed		
	Total (All)	Partial	Almost- Complete	Complete
Fail-to-run	61	46	10	5
Fail-to-start	45	22	11	12
Total	106	68	21	17

5.3 Summary of European Events

In many areas, the European EDG CCF events are similar to the USA EDG CCF events. Several European EDG CCF events led to severe unavailability of the EDGs and illustrate the diversity of the CCF failure mechanisms observed throughout the industry. Additionally, they are also similar to events observed in the USA.

The European EDG CCF event narratives were reviewed to identify observed failures that could provide lessons learned for the USA. A selection of these events is listed below:

- Insufficiently torqued screw in connection blocks of various circuits caused poor connections. The insufficiently torqued screws were due to the location of the screws being difficult to get a torque wrench on and improper tools were used.

- Snow blocked the combustion air intake.

- Low-quality fuel oil led to the failure of the injection pumps.

- Testing procedure inappropriately required the operator to lock out both EDGs.

- Operator locked out both the duty and standby fuel oil tanks in preparation for accepting a fuel oil delivery.

- Maintenance confused the EDGs and performed maintenance on the wrong one, leading to the unavailability of both.

- Testing of fire protection equipment led to three EDGs unavailable.

- During an unrelated modification, an EDG signal cable was cut leading to the unavailability of both EDGs.

- Initial design errors of the pistons and piston rings.

- Fuel pump shaft coupling pins sheared leading to the unavailability of both EDGs.

5.4 Comparison of USA and European Experience

In this section we compare the distributions of the CCF events from the USA and the European countries for failure mode, proximate cause, method of discovery, and sub-system.

The most common EDG configurations in Europe are either two or four. Over 85 percent of the CCF events come from these configuration sizes. Less than 5 percent of the events come from configurations containing five or more EDGs.

Figure 5-1 shows the comparison for failure mode. These failure mode distributions for all events from the USA and Europe are very similar. Figure 5-2 shows that the failure mode distributions are different when restricted to the set of Complete CCF events.

Figure 5-3shows the proximate cause distributions for all events. The most common-cause category for the combined USA and European events is Design/Construction/Installation/Manufacture Inadequacy. The data suggest that Europe has more events due to human error than the USA and that the USA has more component failures than the Europeans do. Figure 5-4 shows the distributions for complete events.

Figure 5-5 shows the method of discovery distributions. The most common discovery method was testing for both the USA and European data sets. No important differences are identified for these distributions. Figure 5-6 shows the distribution for complete CCF events.

Figure 5-7 shows the comparison by sub-system. In Europe, most EDG events occur in the cooling, fuel oil, and engine sub-systems. In the USA, most CCF events occur in the instrumentation and control sub-system, followed by the engine, fuel-oil, generator, and cooling sub-systems. Figure 5-8 shows the distribution for Complete events.

Some interesting points from the analysis of the charts in this section:

- When all events are considered, the human error is much higher for the European data than for the USA data. When Complete events are considered, the comparison is much more similar, with the human error being the most important for both sets of data.

- The testing method of discovery is overwhelmingly important for both the European and USA data.

- The instrumentation and control sub-system contributes less to the all case for the European data than the USA data. But when the Complete case is examined, the instrumentation and control sub-system is the most important for both data sets and the fuel oil sub-system is the next most important.

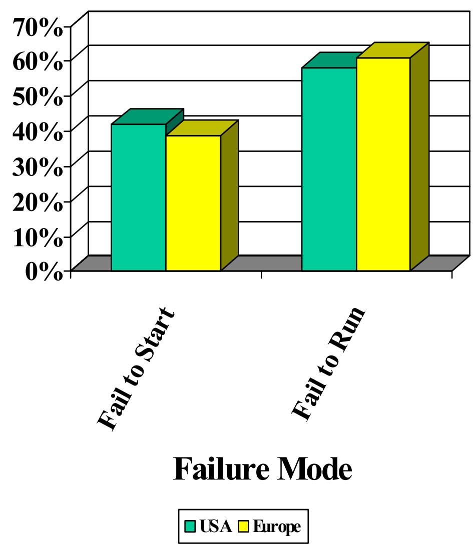

Figure 5-1. Failure mode distributions for all ICDE EDG CCF events.

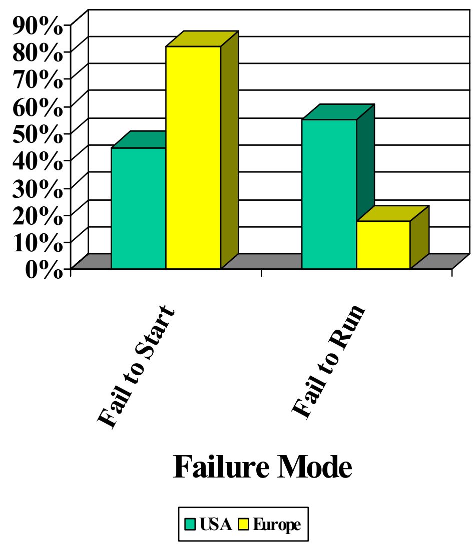

Figure 5-2. Failure mode distribution for Complete ICDE EDG CCF events

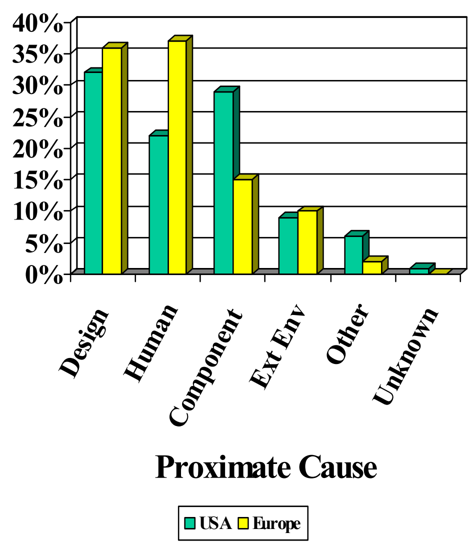

Figure 5-3. Distribution of proximate causes for all ICDE EDG CCF events.

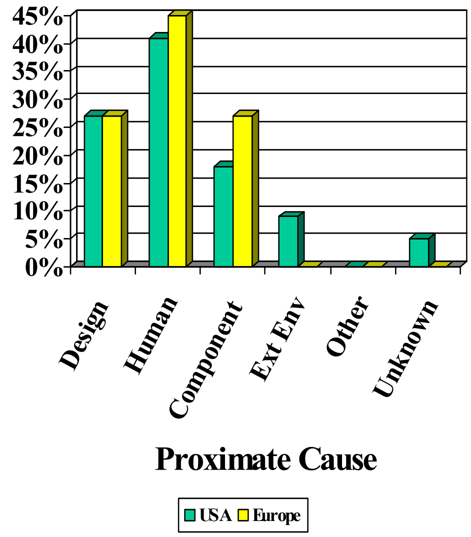

Figure 5-4. Distribution of proximate causes for Complete ICDE CCF EDG events

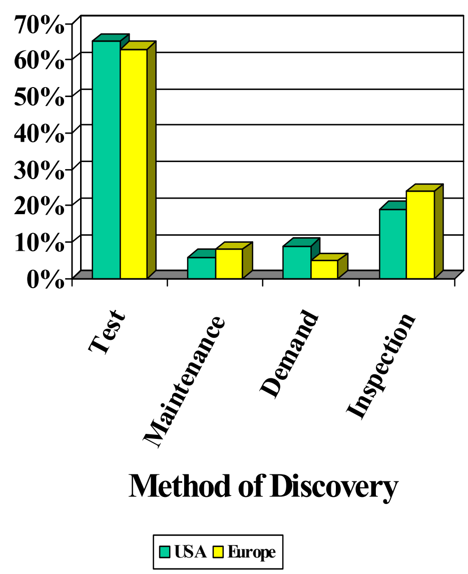

Figure 5-5. Distribution of discovery method for all ICDE EDG CCF events.

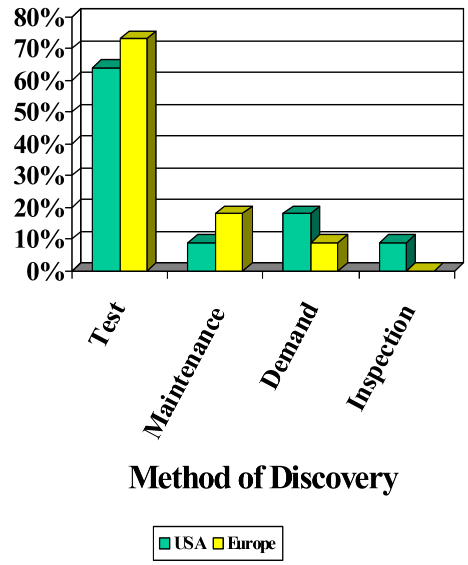

Figure 5-6. Distribution of discovery method for Complete ICDE EDG CCF events

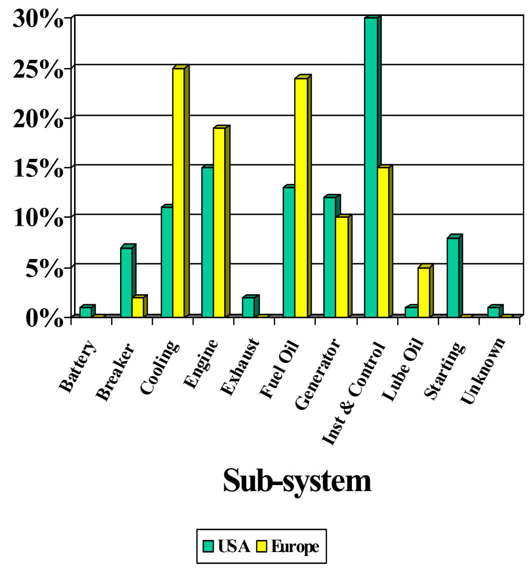

Figure 5-7. Distribution of affected sub-systems for all ICDE EDG CCF events.

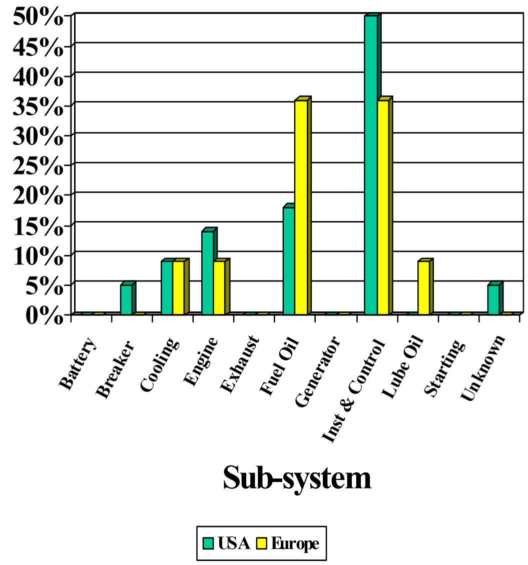

Figure 5-8. Sub-system distribution for Complete ICDE EDG CCF events

6. HOW TO OBTAIN MORE DETAILED INFORMATION

The EDG CCF insights for the U.S. plants are derived from information contained in the CCF Database maintained for the NRC by the INEEL. The database contains CCF-related events that have occurred in U.S. commercial nuclear power plants reported in LERs, NPRDS failure records, and EPIX failure records. The NPRDS and EPIX information is proprietary. Thus, the information presented in the report has been presented in such a way to keep the information proprietary.

The subset of the CCF database presented in this volume is based on the EDG component data from 1980 through 2000. The information contained in the CCF Database consists of coded fields and a descriptive narrative taken verbatim from LERs or NPRDS/EPIX failure records. The database was searched on component type (EDG) and failure mode. The failure modes selected were fail-to-start and fail-to-run. The additional fields, (e.g., proximate cause, coupling factor, shared cause factor, and component degradation values), along with the information contained in the narrative, were used to glean the insights presented in this report. The detailed records and narratives can be obtained from the CCF Database and from respective LERs and NPRDS/EPIX failure records.

The CCF Database was designed so that information can be easily obtained by defining searches. Searches can be made on any coded fields. That is, plant, date, component type, system, proximate cause, coupling factor, shared cause factor, reactor type, reactor vendor, CCCG size, defensive mechanism, degree of failure, or any combination of these coded fields. The results for most of the figures in the report can be obtained or a subset of the information can be obtained by selecting specific values for the fields of interest. The identified records can then be reviewed and reports generated if desired. To obtain access to the NRC CCF Database, contact Dale Rasmuson at the NRC or Ted Wood at the INEEL.

The ICDE project EDG report[11] contains an overview of the international EDG CCF information. Nuclear utilities and NRC staff who desire additional information about the international CCF events can obtain information from Dale Rasmuson, USNRC.

7. REFERENCES

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Appendix A

Data Summary

Appendix A

Data Summary

This appendix is a summary of the data evaluated in the common-cause failure (CCF) data collection effort for EDGs. The tables in this appendix support the charts in Chapter 3. Each table is sorted alphabetically, by the first four columns.

Table A-1. EDG CCF event summary, sorted by proximate cause.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
1	Design/ Construction/ Manufacture/ Installation Inadequacy	Breaker	Test	Logic Circuit	Design	1988	Failure to Start	Almost Complete	A faulty switch contact and incorrect logic circuit design prevented three EDG output breakers from closing. Switches on all EDGs were replaced.
2	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Inspection	Miscellaneous	Design	1997	Failure to Run	Partial	Emergency Diesel Generators testing identified elevated EDG radiator, control and engine room air temperatures. This increase is due to a portion of the radiator discharge air released to atmosphere from the roof of each EDG building being recirculated back into the EDG radiator room.
3	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Inspection	Piping	Design	1988	Failure to Run	Partial	EDG configuration of a diffuser plate allowed sufficient movement to initiate fatigue failure. After failure, the plate contacted the intercooler tubes causing fretting.
4	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Test	Piping	Design	1995	Failure to Run	Almost Complete	Both EDGs failed surveillance test runs due to overheating of the governor oil. Insufficient cooling flow was available because of a design error in pipe size.
5	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Test	Pump	Design	1996	Failure to Run	Almost Complete	Inadequate design left exposed cooling water piping, which freezes in winter.
6	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Test	Valve	Design	1988	Failure to Run	Partial	High lube oil temperature was caused by failed power elements in temperature control valves.
7	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Inspection	Bearing	Operational	1981	Failure to Run	Partial	A crankshaft bearing was wiped and another crankshaft bearing had a crack. Extended operations could cause bearing failure. The wiped journal surface was caused by high temperature from inadequate lubrication.
8	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Inspection	Fuel Nozzles	Quality	1991	Failure to Run	Partial	Cracked fuel injector nozzle tips were found in EDGs. The cracks were due to inadequate ligament thickness and excessive nitriding depth.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
9	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Inspection	Valve	Design	1997	Failure to Start	Partial	Valve adjustment assemblies cracked, manufacturing defect.
10	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Maintenance	Shaft	Design	1986	Failure to Run	Partial	The floating bushing of the idler gear was found with small cracks and frozen to the stub shaft on one EDG, and found with a through-wall crack on another EDG. Cracks were caused by fast starts without full main lube oil pressure, due to the design of the system.
11	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Miscellaneous	Design	1990	Failure to Run	Partial	All three EDGs were underrated for full emergency design loads. Previous testing did not detect the problem due to relatively low ambient temperatures.
12	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Piping	Design	1995	Failure to Run	Partial	A leak was detected in the jacket water cooling system. A system fitting had failed as a result of an inadequate design. Vibration fatigue resulted in cracking.
13	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Shaft	Quality	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.
14	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Shaft	Quality	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.
15	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Turbocharger	Quality	1995	Failure to Run	Partial	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
16	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Turbocharger	Quality	1995	Failure to Run	Complete	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
17	Design/ Construction/ Manufacture/ Installation Inadequacy	Exhaust	Test	Valve	Quality	1991	Failure to Run	Partial	The exhaust damper roll pins failed resulting in the failure of the dampers to open. The cause of pin failure determined to be a manufacturing error.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
18	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Inspection	Tank	Design	1994	Failure to Run	Partial	Inaccurate level instrumentation resulted in less than required fuel inventory. A design error in level instruments was identified. Contributing factors included human error and procedural deficiencies.
19	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Test	Pump	Design	1998	Failure to Start	Almost Complete	EDGs fail to start. The cause of the failure was loss of pump prime due to air entering around the fuel oil booster pump shaft seals.
20	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Test	Pump	Design	1991	Failure to Run	Partial	There was a cracked fitting on a fuel oil pump. The cause of the event was attributed to the delivery valve holder design, which is prone to cracking.
21	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Inspection	Rotor	Quality	1985	Failure to Run	Almost Complete	Cracks were found in the interpolar connections of the damper windings on the rotor poles of the generator. One of the connectors broke during overspeed testing causing substantial damage to the stator. These connectors were not necessary, so they were removed on both generators.
22	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Maintenance	Generator Excitation	Design	1985	Failure to Start	Partial	There was material incompatibility in the voltage regulator.
23	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Relay	Design	1991	Failure to Run	Almost Complete	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.
24	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Relay	Design	1991	Failure to Run	Partial	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.
25	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Rotor	Design	1984	Failure to Run	Partial	A design fault in application of insulation led to rotor damage.
26	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Voltage Regulator	Design	1991	Failure to Start	Partial	Due to the sizing of the power potential transformers and the current transformers, there existed a small area within the leading kVAR range of the generator capability curve in which the voltage regulator would not function.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
27	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Voltage Regulator	Environmental	1990	Failure to Run	Almost Complete	EDG voltage regulator failed due to a partially failed transistor in the static exciter circuit. This was due to a high temperature in the control cabinet. Other EDG equipment susceptible to same conditions due to identical design.
28	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Demand	Governor	Design	1987	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
29	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Demand	Governor	Design	1987	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
30	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Demand	Relay	Quality	1984	Failure to Start	Complete	Relay trips were caused by failed zener diodes in surge protection, which had been installed backwards. The relays were replaced with relays without zener diodes.
31	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Inspection	Miscellaneous	Maintenance	1991	Failure to Start	Almost Complete	One EDG failed to start due to a defective crimp. Defective crimps were found in the other EDGs. Inadequate training, procedures, and QA.
32	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Inspection	Relay	Design	1995	Failure to Start	Almost Complete	A wiring error was discovered, which would prevent the EDG output breakers from closing to a de-energized bus. The error in wiring was the result of an incorrect drawing in a design modification package.
33	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Maintenance	Sensors	Design	1988	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
34	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Maintenance	Sensors	Design	1988	Failure to Run	Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
35	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Fuse	Design	1992	Failure to Start	Complete	A simulated CO2 actuation blew the fuse in the EDG control panel. The condition resulted from a design deficiency during installation of the CO2 system.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
36	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Generator Excitation	Quality	1994	Failure to Start	Partial	Both EDGs were found incapable of carrying design load. Previous governor modifications were identified as the cause. A misadjusted engine governor output linkage and engine performance degradation limited the EDG output.
37	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Governor	Quality	1992	Failure to Run	Partial	Performing EDG monthly load test when governor instabilities noticed. Air trapped in the governor compensation system caused vibrations.
38	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Load Sequencer	Design	1993	Failure to Start	Complete	Diesel sequencers did not load during test. The cause was inadequate design understanding and inadequate post-modification testing.
39	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Miscellaneous	Design	1985	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
40	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Miscellaneous	Design	1985	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
41	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Miscellaneous	Maintenance	1983	Failure to Run	Complete	Breakers tripped on over-current. Incorrect bulb-type indication was installed in the local panel.
42	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Relay	Quality	1991	Failure to Start	Partial	A 240/480 Vac starting contactor coil was in systems designed for 250VDC, which caused control relay arcing across contacts preventing an automatic restart of the EDGs.
43	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Inspection	Valve	Design	1994	Failure to Start	Partial	The air regulator setpoint drifted up. The cause was attributed to selection of the wrong component. All regulators were replaced with a different model.
44	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Test	Valve	Quality	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
45	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Test	Valve	Design	1998	Failure to Start	Partial	EDG potential for a start failure due to the air start solenoid valves not operating consistently below 90 vdc and below 200 psig
46	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Test	Valve	Quality	1990	Failure to Start	Partial	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.
47	External Environment	Cooling	Inspection	Heat Exchanger	Environmental	1995	Failure to Run	Partial	Epoxy paint detached from the inside of the cooling water piping and plugged the heat exchanger.
48	External Environment	Cooling	Test	Miscellaneous	Environmental	1985	Failure to Start	Almost Complete	Due to exceptionally cold temperatures outside the EDG room, the cooling water temperature was too low. One EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. And another EDG was removed from maintenance and tested, when it then tripped on reverse power and engine vibration after starting.
49	External Environment	Cooling	Test	Piping	Design	1990	Failure to Run	Almost Complete	Two of three of the emergency diesel generators had a jacket water leak due to a nipple failure. The cause of the crack has been attributed to a vibration-induced fatigue.
50	External Environment	Fuel Oil	Test	Piping	Design	1981	Failure to Run	Complete	EDG fuel supply hose developed a leak due to excessive localized flexure and vibration. Following repair, EDG tripped due to low control air pressure caused by fitting loosened by engine vibration. Another EDG fuel injector supply line failed due to metal fatigue and vibration.
51	External Environment	Generator	Test	Generator Excitation	Design	1993	Failure to Run	Almost Complete	Both EDGs failed to continue running 22 hours into 24-hour test due to a short on voltage suppression devices due to inadequate cooling in excitation cabinet.
52	External Environment	Inst & Control	Test	Governor	Design	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
53	External Environment	Inst & Control	Test	Governor	Design	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
54	External Environment	Inst & Control	Test	Governor	Environmental	1995	Failure to Run	Partial	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
55	External Environment	Inst & Control	Test	Governor	Environmental	1995	Failure to Run	Complete	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
56	External Environment	Inst & Control	Test	Miscellaneous	Environmental	1985	Failure to Run	Almost Complete	An EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. Another EDG tripped on reverse power and engine vibration, after starting. The cause was attributed to the cold outside temperature (-10 degrees F) with non-functioning outside air supply dampers causing low temperatures in the diesel bays. Also, the service water to the EDG governors was cold, causing sluggish performance. Corrective actions involved sealing the room from the weather.
57	External Environment	Lube Oil	Inspection	Heat Exchanger	Design	1981	Failure to Run	Partial	The lube-oil sub-system was contaminated by lube oil coolers leaking water into the lube oil.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
58	External Environment	Starting	Test	Valve	Design	1987	Failure to Start	Almost Complete	Air start solenoid valves were inoperable and prevented the EDGs from starting. This was due to accelerated degradation.
59	Internal to Component	Breaker	Demand	Switch	Quality	1987	Failure to Start	Almost Complete	The output breaker would not close due to a deformed spring retainer, which prevented a cell switch from providing the permissive to close the breaker.
60	Internal to Component	Breaker	Inspection	Relay	Design	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
61	Internal to Component	Breaker	Inspection	Relay	Design	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
62	Internal to Component	Breaker	Maintenance	Logic Circuit	Design	1986	Failure to Start	Partial	Diesel generator output breakers failed to close during a surveillance check.
63	Internal to Component	Breaker	Test	Relay	Quality	1993	Failure to Start	Partial	The EDG output breaker tripped on reverse power. The EDG tripped on reverse power due to a faulty reverse power relay; the relay was replaced on all EDGs.
64	Internal to Component	Breaker	Test	Switch	Design	1992	Failure to Start	Partial	When the operator attempted to synchronize the emergency diesel generator to offsite power, the output breaker failed to close. The root cause of the EDG output breaker failure to close has been determined to be failure of a switch. A contact pair of the switch lost electrical continuity due to slight breaker movement and/or buildup of oxidation/pitting on the contact surfaces. Switches on all EDGs were replaced.
65	Internal to Component	Cooling	Demand	Valve	Maintenance	1981	Failure to Run	Almost Complete	EDG cooling water check valves malfunctioned, resulting in a loss of cooling.
66	Internal to Component	Cooling	Test	Heat Exchanger	Environmental	1982	Failure to Run	Partial	EDG cooling water inlet and outlet temperatures exceeded allowable valves, due to fouling of the cooling water heat exchanger tubes.
67	Internal to Component	Cooling	Test	Valve	Design	1980	Failure to Run	Complete	Faulty positioners on service water valves in the cooling sub-system led to a failure of all EDGs.
68	Internal to Component	Engine	Inspection	Fuel Rack	Design	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.
69	Internal to Component	Engine	Inspection	Fuel Rack	Design	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.
70	Internal to Component	Engine	Inspection	Fuel Rack	Design	1983	Failure to Run	Partial	Air leakage of the fuel rack assembly was due to a leak through a hole in the exhaust valve diaphragm.
71	Internal to Component	Engine	Test	Governor	Design	1982	Failure to Run	Complete	Failure of the electrical governors was caused by a burnt resistor in the power supply of the control units.
72	Internal to Component	Engine	Test	Piston	Design	1986	Failure to Run	Almost Complete	Failure of the piston wristpin bearings for four cylinders was due to inadequate lube oil film. The other EDG showed existence of similar problems.
73	Internal to Component	Engine	Test	Sensors	Design	1984	Failure to Run	Complete	EDG trips occurred due to an out of calibration temperature switch, leaking air start valve gasket, clearing of lube oil strainer, cleaning of air ejector, problem with air start distributor, out of calibration pressure switch and shattered/leaking piston.
74	Internal to Component	Engine	Test	Turbocharger	Design	1983	Failure to Run	Partial	Vibration resulted in failure of the turbocharger mounting bolts.
75	Internal to Component	Engine	Test	Valve	Maintenance	1998	Failure to Run	Almost Complete	One EDG had broken exhaust valve insert and the other had a sticking exhaust valve. Both EDGs lost compression in the affected cylinder. Both EDGs ran for some time before failure to carry load.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
76	Internal to Component	Exhaust	Test	Valve	Environmental	1987	Failure to Run	Partial	There was a residue in the exhaust damper operator due to water in the instrument air system resulting in the failure of the dampers to open.
77	Internal to Component	Fuel Oil	Demand	Pump	Design	1983	Failure to Run	Partial	Minor fuel oil leaks occurred on pumps.
78	Internal to Component	Fuel Oil	Test	Miscellaneous	Maintenance	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.
79	Internal to Component	Fuel Oil	Test	Miscellaneous	Maintenance	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.
80	Internal to Component	Fuel Oil	Test	Pump	Maintenance	1983	Failure to Run	Partial	Fuel pump belts were broken due to normal wear.
81	Internal to Component	Fuel Oil	Test	Strainer	Environmental	1988	Failure to Run	Partial	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores
82	Internal to Component	Fuel Oil	Test	Strainer	Environmental	1988	Failure to Run	Almost Complete	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores
83	Internal to Component	Generator	Test	Power Resistor	Maintenance	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
84	Internal to Component	Generator	Test	Power Resistor	Maintenance	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
85	Internal to Component	Generator	Test	Power Resistor	Maintenance	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
86	Internal to Component	Inst & Control	Demand	Relay	Design	1980	Failure to Start	Complete	During attempts to shutdown the EDGs, the lockout relays were damaged, thereby making the EDGs inoperable.
87	Internal to Component	Inst & Control	Test	Fuse	Maintenance	1980	Failure to Start	Partial	EDG tripped on overspeed due to two blown control power fuses. Another EDG was inoperable when an inappropriate recorder caused a control power fuse to blow.
88	Internal to Component	Inst & Control	Test	Piping	Design	1980	Failure to Run	Partial	EDG tripped due to a fitting on the control air system vibrating loose, bleeding of holding pressure to the master shutdown valve. Another EDG tripped due to an air leak on the supply line fitting to fuel shutoff pistons causing the fuel control linkage to go to zero fuel position.
89	Internal to Component	Inst & Control	Test	Relay	Maintenance	1982	Failure to Start	Partial	EDG speed could not be manually increased due to a slightly dirty contact on the mode switch or relay. Another EDG start circuit failed due to a speed-sensing relay burned contact stuck in closed position.
90	Internal to Component	Inst & Control	Test	Relay	Maintenance	1998	Failure to Start	Almost Complete	Both EDGs failed due to faulty starting sequence relays. Loose contacts and high contact resistance were the causes.
91	Internal to Component	Inst & Control	Test	Relay	Design	1980	Failure to Start	Complete	During the performance of a pre-operational test, the safety injection signal to the EDGs was picked up. Both EDGs at one unit did not start.
92	Internal to Component	Inst & Control	Test	Sensors	Design	1982	Failure to Run	Partial	One EDG was manually shut down on low water pressure alarm, and another EDG tripped on low cooling water pressure. Both failures were caused by a bad low cooling water pressure switch.
93	Internal to Component	Inst & Control	Test	Valve	Maintenance	1991	Failure to Start	Almost Complete	Foreign material in air control system check valves caused shutdown of two EDGs.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
94	Internal to Component	Inst & Control	Test	Voltage Regulator	Design	1982	Failure to Start	Partial	EDG tripped on overvoltage due to generator output voltage increasing too fast with respect to frequency. Setting on voltage regulator changed. Another EDG tripped on overvoltage due to an incorrect setting on the voltage regulator and a relay picking up lower than expected. Another EDG tripped due to failed speed sensing circuit device that is the frequency to voltage converter.
95	Internal to Component	Starting	Test	Miscellaneous	Maintenance	1982	Failure to Start	Almost Complete	There were nine air start problems on an EDG. Problems ranged from low pressure to air start valve failures and occurred on all three diesel generators.
96	Internal to Component	Starting	Test	Motor	Design	1981	Failure to Start	Partial	Three EDGs air start motors failed to develop minimum rotational speed due to wear, dirt, and grit in the air start system.
97	Internal to Component	Starting	Test	Strainer	Environmental	1985	Failure to Start	Almost Complete	EDG did not start because the fuel racks did not open to supply fuel before the 15-second incomplete sequence timer tripped off. Oil was found in the air start system and a residue of lubricant was on the starting air header filters. Similar conditions were found on the B EDG.
98	Internal to Component	Starting	Test	Valve	Design	1983	Failure to Start	Partial	EDGs failed to auto-start after tripping, due to the shutdown solenoid sticking in the shutdown position.
99	Internal to Component	Starting	Test	Valve	Environmental	1986	Failure to Start	Partial	Failure of air solenoid valves in the EDG air start systems to fully close due to corrosion products prevented the air-start motor from disengaging during starts.
100	Operational/ Human Error	Breaker	Demand	Relay	Maintenance	1991	Failure to Start	Almost Complete	The EDGs did not automatically pick up the load of the 480V busses because the unit trip lockout relays were reset.
101	Operational/ Human Error	Breaker	Test	Switch	Maintenance	1984	Failure to Start	Complete	All of the EDGs at one unit did not automatically start due to a misalignment during breaker line-up. The wrong DC knife switches were opened, thereby failing the EDG start relays.
102	Operational/ Human Error	Cooling	Maintenance	Valve	Maintenance	1993	Failure to Run	Complete	Incorrect installation of pilot solenoid valves was caused by a lack of procedural adherence due to personnel error. Contributing causes were procedural inadequacies, inattention to detail, and inadequate skills.
103	Operational/ Human Error	Cooling	Test	Heat Exchanger	Environmental	1984	Failure to Run	Almost Complete	EDG overheated due to no cooling water flow caused by clam shells on the inlet tube sheet of the first cooler. No flow also found to other EDGs. Clam growth caused by inadequate chlorination, followed by high chlorination that released shells into the system.
104	Operational/ Human Error	Cooling	Test	Heat Exchanger	Environmental	1994	Failure to Run	Partial	Elevated temperatures and frequency swings were observed. Clogging of the heat exchangers by zebra mussels was the cause of the high temperatures. Inspection revealed 50% plugging.
105	Operational/ Human Error	Cooling	Test	Valve	Operational	1990	Failure to Run	Almost Complete	Service water throttle valves were not open enough because the reference used by operators was different from the reference used by engineering staff during flow balances.
106	Operational/ Human Error	Engine	Inspection	Bearing	Maintenance	1980	Failure to Run	Partial	The EDG lower crankshaft main thrust bearing was found wiped due to low lube oil level. Subsequent inspection of other EDG revealed same problem. Dipstick markings were changed.
107	Operational/ Human Error	Engine	Inspection	Piston	Maintenance	1990	Failure to Run	Partial	Sand was found in the lube oil due to sandblasting where the sand entered through the intake. This event led to scoring of the cylinder walls.
108	Operational/ Human Error	Engine	Test	Piston	Maintenance	1989	Failure to Run	Partial	Piston rings failed due to inadequate maintenance procedures.
109	Operational/ Human Error	Fuel Oil	Demand	Pump	Maintenance	1993	Failure to Run	Partial	Fuel oil transfer pump for EDG did not start due to a blown fuse. The fuel oil transfer pump for another EDG was also failed due to a metal piece found between contacts in the low-level cutoff switch.
110	Operational/ Human Error	Fuel Oil	Inspection	Pump	Maintenance	1994	Failure to Run	Almost Complete	Fuel transfer pumps were inoperable due to improper greasing of motor bearings during cold weather operations.
111	Operational/ Human Error	Fuel Oil	Inspection	Tank	Maintenance	1986	Failure to Run	Complete	An operator drained all fuel oil day tanks while sampling the fuel oil.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
112	Operational/ Human Error	Fuel Oil	Inspection	Valve	Maintenance	1983	Failure to Run	Complete	Both fuel oil valves were closed during transfers of fuel, isolating the normal supply from the respective fuel transfer pumps to each of the day tanks.
113	Operational/ Human Error	Fuel Oil	Test	Fuel Rack	Maintenance	1990	Failure to Start	Complete	Fuel rack binding of the fuel rack pivot points was caused by paint, which occurred during painting of the EDGs. The same problem was found on the other EDG, which had been painted at the same time.
114	Operational/ Human Error	Fuel Oil	Test	Piping	Maintenance	1983	Failure to Run	Partial	Maintenance personnel damaged fuel oil tubing, thereby causing leaks.
115	Operational/ Human Error	Fuel Oil	Test	Strainer	Maintenance	1986	Failure to Run	Partial	Maintenance personnel failed to check the fuel filters which led to the failure of one EDG with a plugged filter.
116	Operational/ Human Error	Fuel Oil	Test	Tank	Maintenance	1996	Failure to Run	Partial	Water in fuel oil exceeded tech spec limits for both EDGs.
117	Operational/ Human Error	Fuel Oil	Test	Valve	Maintenance	1986	Failure to Run	Almost Complete	The fuel strainer valves on multiple EDGs were misaligned, thereby restricting fuel oil to the EDGs.
118	Operational/ Human Error	Generator	Test	Logic Circuit	Operational	1982	Failure to Start	Almost Complete	The operator turned the governor controller in the decrease speed direction while paralleling to the bus; that tripped the EDG on reverse power when the operator failed to open the diesel output breaker prior to reaching the reverse power setpoint.
119	Operational/ Human Error	Inst & Control	Demand	Governor	Maintenance	1991	Failure to Start	Almost Complete	Inadequate post maintenance testing was performed following replacement of the governor. This was due to a cognitive error on the part of utility personnel in that an approved work order step, which specified a fast start test of the EDG, was not performed.
120	Operational/ Human Error	Inst & Control	Demand	Relay	Design	1980	Failure to Start	Complete	All EDGs started on an inadvertent SIAS (technician error) during testing. The licensed operator stopped the EDGs prior to the SIAS reset, causing EDGs to be inoperable.
121	Operational/ Human Error	Inst & Control	Demand	Relay	Design	1980	Failure to Start	Complete	During surveillance testing, the operator mistakenly caused a blackout signal, causing all EDGs to start. EDGs were stopped, but during restoration process, all were inoperable for approximately 10 minutes.
122	Operational/ Human Error	Inst & Control	Inspection	Fuse	Maintenance	1990	Failure to Start	Partial	Control power fuses were blown on EDG due to poor maintenance practices and less than adequate documentation of the jacket water system and pressure switch.
123	Operational/ Human Error	Inst & Control	Inspection	Governor	Operational	1987	Failure to Start	Almost Complete	Inadequate operating procedures resulted in EDG failures. The load limit knob was not returned to the correct maximum setting following a special test on both EDGs due to mis-communication.
124	Operational/ Human Error	Inst & Control	Inspection	Relay	Maintenance	1984	Failure to Start	Partial	A review of the protective relay calibration sheet identified that both EDG differential relays were out-of-tolerance.
125	Operational/ Human Error	Inst & Control	Maintenance	Sensors	Maintenance	1983	Failure to Run	Partial	An EDG tripped on reverse current twice during operability testing and another EDG tripped on reverse current once. The cause was attributed to a procedural inadequacy that did not help the operator in avoiding a reverse current trip.
126	Operational/ Human Error	Inst & Control	Test	Load Sequencer	Maintenance	1981	Failure to Start	Complete	Shutdown sequencers to both EDGs failed during testing. One EDG failed due to dirty contacts. The other EDG failed due to a sticking clutch. Both failures were attributed to maintenance and test equipment.
127	Operational/ Human Error	Inst & Control	Test	Relay	Maintenance	1987	Failure to Run	Complete	One EDG stopped during a test run due to an incorrect setpoint on a newly installed phase differential overcurrent relay. Both EDGs had the same setpoint.
128	Operational/ Human Error	Lube Oil	Inspection	Tank	Maintenance	1989	Failure to Run	Almost Complete	Degradation of the EDG lube oil occurred. This was due to the procedure not requiring the immersion heater to be shut off.
129	Operational/ Human Error	Starting	Test	Motor	Maintenance	1993	Failure to Start	Almost Complete	A test procedure required operators to apply air to the distributor while the EDG was running, resulting in damage to the air distributor such that the EDG would not start.

Item	Proximate Cause	Sub-System	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
130	Other	Battery	Test	Battery	Maintenance	1981	Failure to Run	Partial	During surveillance tests, the batteries to both EDGs failed their surveillance tests. The test failures were due to low specific gravity.
131	Other	Generator	Maintenance	Casing	Design	1982	Failure to Run	Partial	Air baffle deformation due to overheating by space heaters caused EDG trips.
132	Other	Generator	Test	Load Sequencer	Design	1981	Failure to Start	Partial	Agastat timer relays setpoint drift and faulty relays resulted in EDG failures.
133	Other	Generator	Test	Voltage Regulator	Design	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.
134	Other	Generator	Test	Voltage Regulator	Design	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.
135	Other	Inst & Control	Inspection	Fuse	Design	1982	Failure to Start	Partial	An EDG power fuse in the control circuitry blew when a broken lead on the annunciator horn shorted to the case. Another EDG power fuse blew, when a burned out bulb on the control board was replaced and the new bulb shattered, thereby shorting the filaments.
136	Other	Inst & Control	Test	Governor	Design	1991	Failure to Run	Partial	An EDG exhibited erratic load control due to intermittent failure of the governor electronic control unit; later, after returning to service, the other EDG tripped on reverse power also caused by failure of the governor control unit.
137	Other	Inst & Control	Test	Relay	Design	1982	Failure to Start	Almost Complete	This event resulted from intermittent failures of the diesel low lube oil pressure start time relay. The relay would prematurely time out before actual pressure was above the low trip setpoint during initial starting of the diesel. This occurred in three of four EDGs and was a failure-to-start. It was detected during testing.
138	Other	Lube Oil	Inspection	Check Valve	Design	1996	Failure to Start	Partial	Leaking lube oil check valves render EDGs inoperable.

Table A-2. EDG CCF event summary, sorted by coupling factor.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
1	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Breaker	Test	Logic Circuit	1988	Failure to Start	Almost Complete	A faulty switch contact and incorrect logic circuit design prevented three EDG output breakers from closing. Switches on all EDGs were replaced.
2	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Inspection	Piping	1988	Failure to Run	Partial	EDG configuration of a diffuser plate allowed sufficient movement to initiate fatigue failure. After failure, the plate contacted the intercooler tubes causing fretting.
3	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Inspection	Miscellaneous	1997	Failure to Run	Partial	Emergency Diesel Generators testing identified elevated EDG radiator, control and engine room air temperatures. This increase is due to a portion of the radiator discharge air released to atmosphere from the roof of each EDG building being recirculated back into the EDG radiator room.
4	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Test	Piping	1995	Failure to Run	Almost Complete	Both EDGs failed surveillance test runs due to overheating of the governor oil. Insufficient cooling flow was available because of a design error in pipe size.
5	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Test	Pump	1996	Failure to Run	Almost Complete	Inadequate design left exposed cooling water piping, which freezes in winter.
6	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Test	Valve	1988	Failure to Run	Partial	High lube oil temperature was caused by failed power elements in temperature control valves.
7	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Inspection	Valve	1997	Failure to Start	Partial	Valve adjustment assemblies cracked, manufacturing defect.
8	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Maintenance	Shaft	1986	Failure to Run	Partial	The floating bushing of the idler gear was found with small cracks and frozen to the stub shaft on one EDG, and found with a through-wall crack on another EDG. Cracks were caused by fast starts without full main lube oil pressure, due to the design of the system.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
9	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Piping	1995	Failure to Run	Partial	A leak was detected in the jacket water cooling system. A system fitting had failed as a result of an inadequate design. Vibration fatigue resulted in cracking.
10	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Miscellaneous	1990	Failure to Run	Partial	All three EDGs were underrated for full emergency design loads. Previous testing did not detect the problem due to relatively low ambient temperatures.
11	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Inspection	Tank	1994	Failure to Run	Partial	Inaccurate level instrumentation resulted in less than required fuel inventory. A design error in level instruments was identified. Contributing factors included human error and procedural deficiencies.
12	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Test	Pump	1998	Failure to Start	Almost Complete	EDGs fail to start. The cause of the failure was loss of pump prime due to air entering around the fuel oil booster pump shaft seals.
13	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Test	Pump	1991	Failure to Run	Partial	There was a cracked fitting on a fuel oil pump. The cause of the event was attributed to the delivery valve holder design, which is prone to cracking.
14	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Maintenance	Generator Excitation	1985	Failure to Start	Partial	There was material incompatibility in the voltage regulator.
15	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Rotor	1984	Failure to Run	Partial	A design fault in application of insulation led to rotor damage.
16	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Relay	1991	Failure to Run	Partial	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.
17	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Voltage Regulator	1991	Failure to Start	Partial	Due to the sizing of the power potential transformers and the current transformers, there existed a small area within the leading kVAR range of the generator capability curve in which the voltage regulator would not function.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
18	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Relay	1991	Failure to Run	Almost Complete	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.
19	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Demand	Governor	1987	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
20	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Demand	Governor	1987	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
21	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Inspection	Relay	1995	Failure to Start	Almost Complete	A wiring error was discovered, which would prevent the EDG output breakers from closing to a de-energized bus. The error in wiring was the result of an incorrect drawing in a design modification package.
22	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Maintenance	Sensors	1988	Failure to Run	Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
23	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Maintenance	Sensors	1988	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
24	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Load Sequencer	1993	Failure to Start	Complete	Diesel sequencers did not load during test. The cause was inadequate design understanding and inadequate post-modification testing.
25	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Fuse	1992	Failure to Start	Complete	A simulated CO2 actuation blew the fuse in the EDG control panel. The condition resulted from a design deficiency during installation of the CO2 system.
26	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Miscellaneous	1985	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
27	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Miscellaneous	1985	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
28	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Inspection	Valve	1994	Failure to Start	Partial	The air regulator setpoint drifted up. The cause was attributed to selection of the wrong component. All regulators were replaced with a different model.
29	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Test	Valve	1998	Failure to Start	Partial	EDG potential for a start failure due to the air start solenoid valves not operating consistently below 90 vdc and below 200 psig
30	Design	External Environment	Cooling	Test	Piping	1990	Failure to Run	Almost Complete	Two of three of the emergency diesel generators had a jacket water leak due to a nipple failure. The cause of the crack has been attributed to a vibration-induced fatigue.
31	Design	External Environment	Fuel Oil	Test	Piping	1981	Failure to Run	Complete	EDG fuel supply hose developed a leak due to excessive localized flexure and vibration. Following repair, EDG tripped due to low control air pressure caused by fitting loosened by engine vibration. Another EDG fuel injector supply line failed due to metal fatigue and vibration.
32	Design	External Environment	Generator	Test	Generator Excitation	1993	Failure to Run	Almost Complete	Both EDGs failed to continue running 22 hours into 24-hour test due to a short on voltage suppression devices due to inadequate cooling in excitation cabinet.
33	Design	External Environment	Inst & Control	Test	Governor	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
34	Design	External Environment	Inst & Control	Test	Governor	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
35	Design	External Environment	Lube Oil	Inspection	Heat Exchanger	1981	Failure to Run	Partial	The lube-oil sub-system was contaminated by lube oil coolers leaking water into the lube oil.
36	Design	External Environment	Starting	Test	Valve	1987	Failure to Start	Almost Complete	Air start solenoid valves were inoperable and prevented the EDGs from starting. This was due to accelerated degradation.
37	Design	Internal to Component	Breaker	Inspection	Relay	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
38	Design	Internal to Component	Breaker	Inspection	Relay	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
39	Design	Internal to Component	Breaker	Maintenance	Logic Circuit	1986	Failure to Start	Partial	Diesel generator output breakers failed to close during a surveillance check.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
40	Design	Internal to Component	Breaker	Test	Switch	1992	Failure to Start	Partial	When the operator attempted to synchronize the emergency diesel generator to offsite power, the output breaker failed to close. The root cause of the EDG output breaker failure to close has been determined to be failure of a switch. A contact pair of the switch lost electrical continuity due to slight breaker movement and/or buildup of oxidation/pitting on the contact surfaces. Switches on all EDGs were replaced.
41	Design	Internal to Component	Cooling	Test	Valve	1980	Failure to Run	Complete	Faulty positioners on service water valves in the cooling sub-system led to a failure of all EDGs.
42	Design	Internal to Component	Engine	Inspection	Fuel Rack	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.
43	Design	Internal to Component	Engine	Inspection	Fuel Rack	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.
44	Design	Internal to Component	Engine	Inspection	Fuel Rack	1983	Failure to Run	Partial	Air leakage of the fuel rack assembly was due to a leak through a hole in the exhaust valve diaphragm.
45	Design	Internal to Component	Engine	Test	Governor	1982	Failure to Run	Complete	Failure of the electrical governors was caused by a burnt resistor in the power supply of the control units.
46	Design	Internal to Component	Engine	Test	Sensors	1984	Failure to Run	Complete	EDG trips occurred due to an out of calibration temperature switch, leaking air start valve gasket, clearing of lube oil strainer, cleaning of air ejector, problem with air start distributor, out of calibration pressure switch and shattered/leaking piston.
47	Design	Internal to Component	Engine	Test	Turbocharger	1983	Failure to Run	Partial	Vibration resulted in failure of the turbocharger mounting bolts.
48	Design	Internal to Component	Engine	Test	Piston	1986	Failure to Run	Almost Complete	Failure of the piston wristpin bearings for four cylinders was due to inadequate lube oil film. The other EDG showed existence of similar problems.
49	Design	Internal to Component	Fuel Oil	Demand	Pump	1983	Failure to Run	Partial	Minor fuel oil leaks occurred on pumps.
50	Design	Internal to Component	Inst & Control	Demand	Relay	1980	Failure to Start	Complete	During attempts to shutdown the EDGs, the lockout relays were damaged, thereby making the EDGs inoperable.
51	Design	Internal to Component	Inst & Control	Test	Sensors	1982	Failure to Run	Partial	One EDG was manually shut down on low water pressure alarm, and another EDG tripped on low cooling water pressure. Both failures were caused by a bad low cooling water pressure switch.
52	Design	Internal to Component	Inst & Control	Test	Piping	1980	Failure to Run	Partial	EDG tripped due to a fitting on the control air system vibrating loose, bleeding of holding pressure to the master shutdown valve. Another EDG tripped due to an air leak on the supply line fitting to fuel shutoff pistons causing the fuel control linkage to go to zero fuel position.
53	Design	Internal to Component	Inst & Control	Test	Voltage Regulator	1982	Failure to Start	Partial	EDG tripped on overvoltage due to generator output voltage increasing too fast with respect to frequency. Setting on voltage regulator changed. Another EDG tripped on overvoltage due to an incorrect setting on the voltage regulator and a relay picking up lower than expected. Another EDG tripped due to failed speed sensing circuit device that is the frequency to voltage converter.
54	Design	Internal to Component	Inst & Control	Test	Relay	1980	Failure to Start	Complete	During the performance of a pre-operational test, the safety injection signal to the EDGs was picked up. Both EDGs at one unit did not start.
55	Design	Internal to Component	Starting	Test	Valve	1983	Failure to Start	Partial	EDGs failed to auto-start after tripping, due to the shutdown solenoid sticking in the shutdown position.
56	Design	Internal to Component	Starting	Test	Motor	1981	Failure to Start	Partial	Three EDGs air start motors failed to develop minimum rotational speed due to wear, dirt, and grit in the air start system.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
57	Design	Operational/ Human Error	Inst & Control	Demand	Relay	1980	Failure to Start	Complete	All EDGs started on an inadvertent SIAS (technician error) during testing. The licensed operator stopped the EDGs prior to the SIAS reset, causing EDGs to be inoperable.
58	Design	Operational/ Human Error	Inst & Control	Demand	Relay	1980	Failure to Start	Complete	During surveillance testing, the operator mistakenly caused a blackout signal, causing all EDGs to start. EDGs were stopped, but during restoration process, all were inoperable for approximately 10 minutes.
59	Design	Other	Generator	Maintenance	Casing	1982	Failure to Run	Partial	Air baffle deformation due to overheating by space heaters caused EDG trips.
60	Design	Other	Generator	Test	Voltage Regulator	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.
61	Design	Other	Generator	Test	Voltage Regulator	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.
62	Design	Other	Generator	Test	Load Sequencer	1981	Failure to Start	Partial	Agastat timer relays setpoint drift and faulty relays resulted in EDG failures.
63	Design	Other	Inst & Control	Inspection	Fuse	1982	Failure to Start	Partial	An EDG power fuse in the control circuitry blew when a broken lead on the annunciator horn shorted to the case. Another EDG power fuse blew, when a burned out bulb on the control board was replaced and the new bulb shattered, thereby shorting the filaments.
64	Design	Other	Inst & Control	Test	Relay	1982	Failure to Start	Almost Complete	This event resulted from intermittent failures of the diesel low lube oil pressure start time relay. The relay would prematurely time out before actual pressure was above the low trip setpoint during initial starting of the diesel. This occurred in three of four EDGs and was a failure-to-start. It was detected during testing.
65	Design	Other	Inst & Control	Test	Governor	1991	Failure to Run	Partial	An EDG exhibited erratic load control due to intermittent failure of the governor electronic control unit; later, after returning to service, the other EDG tripped on reverse power also caused by failure of the governor control unit.
66	Design	Other	Lube Oil	Inspection	Check Valve	1996	Failure to Start	Partial	Leaking lube oil check valves render EDGs inoperable.
67	Environmental	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Test	Voltage Regulator	1990	Failure to Run	Almost Complete	EDG voltage regulator failed due to a partially failed transistor in the static exciter circuit. This was due to a high temperature in the control cabinet. Other EDG equipment susceptible to same conditions due to identical design.
68	Environmental	External Environment	Cooling	Inspection	Heat Exchanger	1995	Failure to Run	Partial	Epoxy paint detached from the inside of the cooling water piping and plugged the heat exchanger.
69	Environmental	External Environment	Cooling	Test	Miscellaneous	1985	Failure to Start	Almost Complete	Due to exceptionally cold temperatures outside the EDG room, the cooling water temperature was too low. One EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. And another EDG was removed from maintenance and tested, when it then tripped on reverse power and engine vibration after starting.
70	Environmental	External Environment	Inst & Control	Test	Miscellaneous	1985	Failure to Run	Almost Complete	An EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. Another EDG tripped on reverse power and engine vibration, after starting. The cause was attributed to the cold outside temperature (-10 degrees F) with non-functioning outside air supply dampers causing low temperatures in the diesel bays. Also, the service water to the EDG governors was cold, causing sluggish performance. Corrective actions involved sealing the room from the weather.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
71	Environmental	External Environment	Inst & Control	Test	Governor	1995	Failure to Run	Partial	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
72	Environmental	External Environment	Inst & Control	Test	Governor	1995	Failure to Run	Complete	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
73	Environmental	Internal to Component	Cooling	Test	Heat Exchanger	1982	Failure to Run	Partial	EDG cooling water inlet and outlet temperatures exceeded allowable valves, due to fouling of the cooling water heat exchanger tubes.
74	Environmental	Internal to Component	Exhaust	Test	Valve	1987	Failure to Run	Partial	There was a residue in the exhaust damper operator due to water in the instrument air system resulting in the failure of the dampers to open.
75	Environmental	Internal to Component	Fuel Oil	Test	Strainer	1988	Failure to Run	Almost Complete	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores
76	Environmental	Internal to Component	Fuel Oil	Test	Strainer	1988	Failure to Run	Partial	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores
77	Environmental	Internal to Component	Starting	Test	Strainer	1985	Failure to Start	Almost Complete	EDG did not start because the fuel racks did not open to supply fuel before the 15-second incomplete sequence timer tripped off. Oil was found in the air start system and a residue of lubricant was on the starting air header filters. Similar conditions were found on the B EDG.
78	Environmental	Internal to Component	Starting	Test	Valve	1986	Failure to Start	Partial	Failure of air solenoid valves in the EDG air start systems to fully close due to corrosion products prevented the air-start motor from disengaging during starts.
79	Environmental	Operational/ Human Error	Cooling	Test	Heat Exchanger	1984	Failure to Run	Almost Complete	EDG overheated due to no cooling water flow caused by clam shells on the inlet tube sheet of the first cooler. No flow also found to other EDGs. Clam growth caused by inadequate chlorination, followed by high chlorination that released shells into the system.
80	Environmental	Operational/ Human Error	Cooling	Test	Heat Exchanger	1994	Failure to Run	Partial	Elevated temperatures and frequency swings were observed. Clogging of the heat exchangers by zebra mussels was the cause of the high temperatures. Inspection revealed 50% plugging.
81	Maintenance	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Inspection	Miscellaneous	1991	Failure to Start	Almost Complete	One EDG failed to start due to a defective crimp. Defective crimps were found in the other EDGs. Inadequate training, procedures, and QA.
82	Maintenance	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Miscellaneous	1983	Failure to Run	Complete	Breakers tripped on over-current. Incorrect bulb-type indication was installed in the local panel.
83	Maintenance	Internal to Component	Cooling	Demand	Valve	1981	Failure to Run	Almost Complete	EDG cooling water check valves malfunctioned, resulting in a loss of cooling.
84	Maintenance	Internal to Component	Engine	Test	Valve	1998	Failure to Run	Almost Complete	One EDG had broken exhaust valve insert and the other had a sticking exhaust valve. Both EDGs lost compression in the affected cylinder. Both EDGs ran for some time before failure to carry load.
85	Maintenance	Internal to Component	Fuel Oil	Test	Miscellaneous	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
86	Maintenance	Internal to Component	Fuel Oil	Test	Pump	1983	Failure to Run	Partial	Fuel pump belts were broken due to normal wear.
87	Maintenance	Internal to Component	Fuel Oil	Test	Miscellaneous	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.
88	Maintenance	Internal to Component	Generator	Test	Power Resistor	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
89	Maintenance	Internal to Component	Generator	Test	Power Resistor	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
90	Maintenance	Internal to Component	Generator	Test	Power Resistor	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
91	Maintenance	Internal to Component	Inst & Control	Test	Fuse	1980	Failure to Start	Partial	EDG tripped on overspeed due to two blown control power fuses. Another EDG was inoperable when an inappropriate recorder caused a control power fuse to blow.
92	Maintenance	Internal to Component	Inst & Control	Test	Relay	1998	Failure to Start	Almost Complete	Both EDGs failed due to faulty starting sequence relays. Loose contacts and high contact resistance were the causes.
93	Maintenance	Internal to Component	Inst & Control	Test	Relay	1982	Failure to Start	Partial	EDG speed could not be manually increased due to a slightly dirty contact on the mode switch or relay. Another EDG start circuit failed due to a speed-sensing relay burned contact stuck in closed position.
94	Maintenance	Internal to Component	Inst & Control	Test	Valve	1991	Failure to Start	Almost Complete	Foreign material in air control system check valves caused shutdown of two EDGs.
95	Maintenance	Internal to Component	Starting	Test	Miscellaneous	1982	Failure to Start	Almost Complete	There were nine air start problems on an EDG. Problems ranged from low pressure to air start valve failures and occurred on all three diesel generators.
96	Maintenance	Operational/ Human Error	Breaker	Demand	Relay	1991	Failure to Start	Almost Complete	The EDGs did not automatically pick up the load of the 480V busses because the unit trip lockout relays were reset.
97	Maintenance	Operational/ Human Error	Breaker	Test	Switch	1984	Failure to Start	Complete	All of the EDGs at one unit did not automatically start due to a misalignment during breaker line-up. The wrong DC knife switches were opened, thereby failing the EDG start relays.
98	Maintenance	Operational/ Human Error	Cooling	Maintenance	Valve	1993	Failure to Run	Complete	Incorrect installation of pilot solenoid valves was caused by a lack of procedural adherence due to personnel error. Contributing causes were procedural inadequacies, inattention to detail, and inadequate skills.
99	Maintenance	Operational/ Human Error	Engine	Inspection	Piston	1990	Failure to Run	Partial	Sand was found in the lube oil due to sandblasting where the sand entered through the intake. This event led to scoring of the cylinder walls.
100	Maintenance	Operational/ Human Error	Engine	Inspection	Bearing	1980	Failure to Run	Partial	The EDG lower crankshaft main thrust bearing was found wiped due to low lube oil level. Subsequent inspection of other EDG revealed same problem. Dipstick markings were changed.
101	Maintenance	Operational/ Human Error	Engine	Test	Piston	1989	Failure to Run	Partial	Piston rings failed due to inadequate maintenance procedures.
102	Maintenance	Operational/ Human Error	Fuel Oil	Demand	Pump	1993	Failure to Run	Partial	Fuel oil transfer pump for EDG did not start due to a blown fuse. The fuel oil transfer pump for another EDG was also failed due to a metal piece found between contacts in the low-level cutoff switch.
103	Maintenance	Operational/ Human Error	Fuel Oil	Inspection	Valve	1983	Failure to Run	Complete	Both fuel oil valves were closed during transfers of fuel, isolating the normal supply from the respective fuel transfer pumps to each of the day tanks.
104	Maintenance	Operational/ Human Error	Fuel Oil	Inspection	Tank	1986	Failure to Run	Complete	An operator drained all fuel oil day tanks while sampling the fuel oil.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
105	Maintenance	Operational/ Human Error	Fuel Oil	Inspection	Pump	1994	Failure to Run	Almost Complete	Fuel transfer pumps were inoperable due to improper greasing of motor bearings during cold weather operations.
106	Maintenance	Operational/ Human Error	Fuel Oil	Test	Valve	1986	Failure to Run	Almost Complete	The fuel strainer valves on multiple EDGs were misaligned, thereby restricting fuel oil to the EDGs.
107	Maintenance	Operational/ Human Error	Fuel Oil	Test	Strainer	1986	Failure to Run	Partial	Maintenance personnel failed to check the fuel filters which led to the failure of one EDG with a plugged filter.
108	Maintenance	Operational/ Human Error	Fuel Oil	Test	Tank	1996	Failure to Run	Partial	Water in fuel oil exceeded tech spec limits for both EDGs.
109	Maintenance	Operational/ Human Error	Fuel Oil	Test	Fuel Rack	1990	Failure to Start	Complete	Fuel rack binding of the fuel rack pivot points was caused by paint, which occurred during painting of the EDGs. The same problem was found on the other EDG, which had been painted at the same time.
110	Maintenance	Operational/ Human Error	Fuel Oil	Test	Piping	1983	Failure to Run	Partial	Maintenance personnel damaged fuel oil tubing, thereby causing leaks.
111	Maintenance	Operational/ Human Error	Inst & Control	Demand	Governor	1991	Failure to Start	Almost Complete	Inadequate post maintenance testing was performed following replacement of the governor. This was due to a cognitive error on the part of utility personnel in that an approved work order step, which specified a fast start test of the EDG, was not performed.
112	Maintenance	Operational/ Human Error	Inst & Control	Inspection	Relay	1984	Failure to Start	Partial	A review of the protective relay calibration sheet identified that both EDG differential relays were out-of-tolerance.
113	Maintenance	Operational/ Human Error	Inst & Control	Inspection	Fuse	1990	Failure to Start	Partial	Control power fuses were blown on EDG due to poor maintenance practices and less than adequate documentation of the jacket water system and pressure switch.
114	Maintenance	Operational/ Human Error	Inst & Control	Maintenance	Sensors	1983	Failure to Run	Partial	An EDG tripped on reverse current twice during operability testing and another EDG tripped on reverse current once. The cause was attributed to a procedural inadequacy that did not help the operator in avoiding a reverse current trip.
115	Maintenance	Operational/ Human Error	Inst & Control	Test	Relay	1987	Failure to Run	Complete	One EDG stopped during a test run due to an incorrect setpoint on a newly installed phase differential overcurrent relay. Both EDGs had the same setpoint.
116	Maintenance	Operational/ Human Error	Inst & Control	Test	Load Sequencer	1981	Failure to Start	Complete	Shutdown sequencers to both EDGs failed during testing. One EDG failed due to dirty contacts. The other EDG failed due to a sticking clutch. Both failures were attributed to maintenance and test equipment.
117	Maintenance	Operational/ Human Error	Lube Oil	Inspection	Tank	1989	Failure to Run	Almost Complete	Degradation of the EDG lube oil occurred. This was due to the procedure not requiring the immersion heater to be shut off.
118	Maintenance	Operational/ Human Error	Starting	Test	Motor	1993	Failure to Start	Almost Complete	A test procedure required operators to apply air to the distributor while the EDG was running, resulting in damage to the air distributor such that the EDG would not start.
119	Maintenance	Other	Battery	Test	Battery	1981	Failure to Run	Partial	During surveillance tests, the batteries to both EDGs failed their surveillance tests. The test failures were due to low specific gravity.
120	Operational	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Inspection	Bearing	1981	Failure to Run	Partial	A crankshaft bearing was wiped and another crankshaft bearing had a crack. Extended operations could cause bearing failure. The wiped journal surface was caused by high temperature from inadequate lubrication.
121	Operational	Operational/ Human Error	Cooling	Test	Valve	1990	Failure to Run	Almost Complete	Service water throttle valves were not open enough because the reference used by operators was different from the reference used by engineering staff during flow balances.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
122	Operational	Operational/ Human Error	Generator	Test	Logic Circuit	1982	Failure to Start	Almost Complete	The operator turned the governor controller in the decrease speed direction while paralleling to the bus; that tripped the EDG on reverse power when the operator failed to open the diesel output breaker prior to reaching the reverse power setpoint.
123	Operational	Operational/ Human Error	Inst & Control	Inspection	Governor	1987	Failure to Start	Almost Complete	Inadequate operating procedures resulted in EDG failures. The load limit knob was not returned to the correct maximum setting following a special test on both EDGs due to mis-communication.
124	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Inspection	Fuel Nozzles	1991	Failure to Run	Partial	Cracked fuel injector nozzle tips were found in EDGs. The cracks were due to inadequate ligament thickness and excessive nitriding depth.
125	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Shaft	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.
126	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Turbocharger	1995	Failure to Run	Partial	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
127	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Turbocharger	1995	Failure to Run	Complete	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
128	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Test	Shaft	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.
129	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Exhaust	Test	Valve	1991	Failure to Run	Partial	The exhaust damper roll pins failed resulting in the failure of the dampers to open. The cause of pin failure determined to be a manufacturing error.
130	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Inspection	Rotor	1985	Failure to Run	Almost Complete	Cracks were found in the interpolar connections of the damper windings on the rotor poles of the generator. One of the connectors broke during overspeed testing causing substantial damage to the stator. These connectors were not necessary, so they were removed on both generators.
131	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Demand	Relay	1984	Failure to Start	Complete	Relay trips were caused by failed zener diodes in surge protection, which had been installed backwards. The relays were replaced with relays without zener diodes.

Item	Coupling Factor	Proximate Cause	Sub-System	Discovery Method	Piece Part	Year	Failure Mode	Degree of Failure	Description
132	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Governor	1992	Failure to Run	Partial	Performing EDG monthly load test when governor instabilities noticed. Air trapped in the governor compensation system caused vibrations.
133	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Generator Excitation	1994	Failure to Start	Partial	Both EDGs were found incapable of carrying design load. Previous governor modifications were identified as the cause. A misadjusted engine governor output linkage and engine performance degradation limited the EDG output.
134	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Test	Relay	1991	Failure to Start	Partial	A 240/480 Vac starting contactor coil was in systems designed for 250VDC, which caused control relay arcing across contacts preventing an automatic restart of the EDGs.
135	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Test	Valve	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.
136	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Test	Valve	1990	Failure to Start	Partial	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.
137	Quality	Internal to Component	Breaker	Demand	Switch	1987	Failure to Start	Almost Complete	The output breaker would not close due to a deformed spring retainer, which prevented a cell switch from providing the permissive to close the breaker.
138	Quality	Internal to Component	Breaker	Test	Relay	1993	Failure to Start	Partial	The EDG output breaker tripped on reverse power. The EDG tripped on reverse power due to a faulty reverse power relay; the relay was replaced on all EDGs.

Table A-3. EDG CCF event summary, sorted by discovery method.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
1	Demand	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Governor	1987	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
2	Demand	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Governor	1987	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
3	Demand	Design	Internal to Component	Fuel Oil	Pump	1983	Failure to Run	Partial	Minor fuel oil leaks occurred on pumps.
4	Demand	Design	Internal to Component	Inst & Control	Relay	1980	Failure to Start	Complete	During attempts to shutdown the EDGs, the lockout relays were damaged, thereby making the EDGs inoperable.
5	Demand	Design	Operational/ Human Error	Inst & Control	Relay	1980	Failure to Start	Complete	All EDGs started on an inadvertent SIAS (technician error) during testing. The licensed operator stopped the EDGs prior to the SIAS reset, causing EDGs to be inoperable.
6	Demand	Design	Operational/ Human Error	Inst & Control	Relay	1980	Failure to Start	Complete	During surveillance testing, the operator mistakenly caused a blackout signal, causing all EDGs to start. EDGs were stopped, but during restoration process, all were inoperable for approximately 10 minutes.
7	Demand	Maintenance	Internal to Component	Cooling	Valve	1981	Failure to Run	Almost Complete	EDG cooling water check valves malfunctioned, resulting in a loss of cooling.
8	Demand	Maintenance	Operational/ Human Error	Breaker	Relay	1991	Failure to Start	Almost Complete	The EDGs did not automatically pick up the load of the 480V busses because the unit trip lockout relays were reset.
9	Demand	Maintenance	Operational/ Human Error	Fuel Oil	Pump	1993	Failure to Run	Partial	Fuel oil transfer pump for EDG did not start due to a blown fuse. The fuel oil transfer pump for another EDG was also failed due to a metal piece found between contacts in the low-level cutoff switch.
10	Demand	Maintenance	Operational/ Human Error	Inst & Control	Governor	1991	Failure to Start	Almost Complete	Inadequate post maintenance testing was performed following replacement of the governor. This was due to a cognitive error on the part of utility personnel in that an approved work order step, which specified a fast start test of the EDG, was not performed.
11	Demand	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Relay	1984	Failure to Start	Complete	Relay trips were caused by failed zener diodes in surge protection, which had been installed backwards. The relays were replaced with relays without zener diodes.
12	Demand	Quality	Internal to Component	Breaker	Switch	1987	Failure to Start	Almost Complete	The output breaker would not close due to a deformed spring retainer, which prevented a cell switch from providing the permissive to close the breaker.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
13	Inspection	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Piping	1988	Failure to Run	Partial	EDG configuration of a diffuser plate allowed sufficient movement to initiate fatigue failure. After failure, the plate contacted the intercooler tubes causing fretting.
14	Inspection	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Miscellaneous	1997	Failure to Run	Partial	Emergency Diesel Generators testing identified elevated EDG radiator, control and engine room air temperatures. This increase is due to a portion of the radiator discharge air released to atmosphere from the roof of each EDG building being recirculated back into the EDG radiator room.
15	Inspection	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Valve	1997	Failure to Start	Partial	Valve adjustment assemblies cracked, manufacturing defect.
16	Inspection	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Tank	1994	Failure to Run	Partial	Inaccurate level instrumentation resulted in less than required fuel inventory. A design error in level instruments was identified. Contributing factors included human error and procedural deficiencies.
17	Inspection	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Relay	1995	Failure to Start	Almost Complete	A wiring error was discovered, which would prevent the EDG output breakers from closing to a de-energized bus. The error in wiring was the result of an incorrect drawing in a design modification package.
18	Inspection	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Valve	1994	Failure to Start	Partial	The air regulator setpoint drifted up. The cause was attributed to selection of the wrong component. All regulators were replaced with a different model.
19	Inspection	Design	External Environment	Lube Oil	Heat Exchanger	1981	Failure to Run	Partial	The lube-oil sub-system was contaminated by lube oil coolers leaking water into the lube oil.
20	Inspection	Design	Internal to Component	Breaker	Relay	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
21	Inspection	Design	Internal to Component	Breaker	Relay	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
22	Inspection	Design	Internal to Component	Engine	Fuel Rack	1983	Failure to Run	Partial	Air leakage of the fuel rack assembly was due to a leak through a hole in the exhaust valve diaphragm.
23	Inspection	Design	Internal to Component	Engine	Fuel Rack	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.
24	Inspection	Design	Internal to Component	Engine	Fuel Rack	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
25	Inspection	Design	Other	Inst & Control	Fuse	1982	Failure to Start	Partial	An EDG power fuse in the control circuitry blew when a broken lead on the annunciator horn shorted to the case. Another EDG power fuse blew, when a burned out bulb on the control board was replaced and the new bulb shattered, thereby shorting the filaments.
26	Inspection	Design	Other	Lube Oil	Check Valve	1996	Failure to Start	Partial	Leaking lube oil check valves render EDGs inoperable.
27	Inspection	Environmental	External Environment	Cooling	Heat Exchanger	1995	Failure to Run	Partial	Epoxy paint detached from the inside of the cooling water piping and plugged the heat exchanger.
28	Inspection	Maintenance	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Miscellaneous	1991	Failure to Start	Almost Complete	One EDG failed to start due to a defective crimp. Defective crimps were found in the other EDGs. Inadequate training, procedures, and QA.
29	Inspection	Maintenance	Operational/ Human Error	Engine	Bearing	1980	Failure to Run	Partial	The EDG lower crankshaft main thrust bearing was found wiped due to low lube oil level. Subsequent inspection of other EDG revealed same problem. Dipstick markings were changed.
30	Inspection	Maintenance	Operational/ Human Error	Engine	Piston	1990	Failure to Run	Partial	Sand was found in the lube oil due to sandblasting where the sand entered through the intake. This event led to scoring of the cylinder walls.
31	Inspection	Maintenance	Operational/ Human Error	Fuel Oil	Valve	1983	Failure to Run	Complete	Both fuel oil valves were closed during transfers of fuel, isolating the normal supply from the respective fuel transfer pumps to each of the day tanks.
32	Inspection	Maintenance	Operational/ Human Error	Fuel Oil	Tank	1986	Failure to Run	Complete	An operator drained all fuel oil day tanks while sampling the fuel oil.
33	Inspection	Maintenance	Operational/ Human Error	Fuel Oil	Pump	1994	Failure to Run	Almost Complete	Fuel transfer pumps were inoperable due to improper greasing of motor bearings during cold weather operations.
34	Inspection	Maintenance	Operational/ Human Error	Inst & Control	Relay	1984	Failure to Start	Partial	A review of the protective relay calibration sheet identified that both EDG differential relays were out-of-tolerance.
35	Inspection	Maintenance	Operational/ Human Error	Inst & Control	Fuse	1990	Failure to Start	Partial	Control power fuses were blown on EDG due to poor maintenance practices and less than adequate documentation of the jacket water system and pressure switch.
36	Inspection	Maintenance	Operational/ Human Error	Lube Oil	Tank	1989	Failure to Run	Almost Complete	Degradation of the EDG lube oil occurred. This was due to the procedure not requiring the immersion heater to be shut off.
37	Inspection	Operational	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Bearing	1981	Failure to Run	Partial	A crankshaft bearing was wiped and another crankshaft bearing had a crack. Extended operations could cause bearing failure. The wiped journal surface was caused by high temperature from inadequate lubrication.
38	Inspection	Operational	Operational/ Human Error	Inst & Control	Governor	1987	Failure to Start	Almost Complete	Inadequate operating procedures resulted in EDG failures. The load limit knob was not returned to the correct maximum setting following a special test on both EDGs due to mis-communication.
39	Inspection	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Fuel Nozzles	1991	Failure to Run	Partial	Cracked fuel injector nozzle tips were found in EDGs. The cracks were due to inadequate ligament thickness and excessive nitriding depth.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
40	Inspection	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Rotor	1985	Failure to Run	Almost Complete	Cracks were found in the interpolar connections of the damper windings on the rotor poles of the generator. One of the connectors broke during overspeed testing causing substantial damage to the stator. These connectors were not necessary, so they were removed on both generators.
41	Maintenance	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Shaft	1986	Failure to Run	Partial	The floating bushing of the idler gear was found with small cracks and frozen to the stub shaft on one EDG, and found with a through-wall crack on another EDG. Cracks were caused by fast starts without full main lube oil pressure, due to the design of the system.
42	Maintenance	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Generator Excitation	1985	Failure to Start	Partial	There was material incompatibility in the voltage regulator.
43	Maintenance	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Sensors	1988	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
44	Maintenance	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Sensors	1988	Failure to Run	Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
45	Maintenance	Design	Internal to Component	Breaker	Logic Circuit	1986	Failure to Start	Partial	Diesel generator output breakers failed to close during a surveillance check.
46	Maintenance	Design	Other	Generator	Casing	1982	Failure to Run	Partial	Air baffle deformation due to overheating by space heaters caused EDG trips.
47	Maintenance	Maintenance	Operational/ Human Error	Cooling	Valve	1993	Failure to Run	Complete	Incorrect installation of pilot solenoid valves was caused by a lack of procedural adherence due to personnel error. Contributing causes were procedural inadequacies, inattention to detail, and inadequate skills.
48	Maintenance	Maintenance	Operational/ Human Error	Inst & Control	Sensors	1983	Failure to Run	Partial	An EDG tripped on reverse current twice during operability testing and another EDG tripped on reverse current once. The cause was attributed to a procedural inadequacy that did not help the operator in avoiding a reverse current trip.
49	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Breaker	Logic Circuit	1988	Failure to Start	Almost Complete	A faulty switch contact and incorrect logic circuit design prevented three EDG output breakers from closing. Switches on all EDGs were replaced.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
50	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Pump	1996	Failure to Run	Almost Complete	Inadequate design left exposed cooling water piping, which freezes in winter.
51	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Valve	1988	Failure to Run	Partial	High lube oil temperature was caused by failed power elements in temperature control valves.
52	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Cooling	Piping	1995	Failure to Run	Almost Complete	Both EDGs failed surveillance test runs due to overheating of the governor oil. Insufficient cooling flow was available because of a design error in pipe size.
53	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Miscellaneous	1990	Failure to Run	Partial	All three EDGs were underrated for full emergency design loads. Previous testing did not detect the problem due to relatively low ambient temperatures.
54	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Piping	1995	Failure to Run	Partial	A leak was detected in the jacket water cooling system. A system fitting had failed as a result of an inadequate design. Vibration fatigue resulted in cracking.
55	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Pump	1991	Failure to Run	Partial	There was a cracked fitting on a fuel oil pump. The cause of the event was attributed to the delivery valve holder design, which is prone to cracking.
56	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Fuel Oil	Pump	1998	Failure to Start	Almost Complete	EDGs fail to start. The cause of the failure was loss of pump prime due to air entering around the fuel oil booster pump shaft seals.
57	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Rotor	1984	Failure to Run	Partial	A design fault in application of insulation led to rotor damage.
58	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Relay	1991	Failure to Run	Almost Complete	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
59	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Relay	1991	Failure to Run	Partial	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.
60	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Voltage Regulator	1991	Failure to Start	Partial	Due to the sizing of the power potential transformers and the current transformers, there existed a small area within the leading kVAR range of the generator capability curve in which the voltage regulator would not function.
61	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Miscellaneous	1985	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
62	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Fuse	1992	Failure to Start	Complete	A simulated CO2 actuation blew the fuse in the EDG control panel. The condition resulted from a design deficiency during installation of the CO2 system.
63	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Miscellaneous	1985	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
64	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Load Sequencer	1993	Failure to Start	Complete	Diesel sequencers did not load during test. The cause was inadequate design understanding and inadequate post-modification testing.
65	Test	Design	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Valve	1998	Failure to Start	Partial	EDG potential for a start failure due to the air start solenoid valves not operating consistently below 90 vdc and below 200 psig
66	Test	Design	External Environment	Cooling	Piping	1990	Failure to Run	Almost Complete	Two of three of the emergency diesel generators had a jacket water leak due to a nipple failure. The cause of the crack has been attributed to a vibration-induced fatigue.
67	Test	Design	External Environment	Fuel Oil	Piping	1981	Failure to Run	Complete	EDG fuel supply hose developed a leak due to excessive localized flexure and vibration. Following repair, EDG tripped due to low control air pressure caused by fitting loosened by engine vibration. Another EDG fuel injector supply line failed due to metal fatigue and vibration.
68	Test	Design	External Environment	Generator	Generator Excitation	1993	Failure to Run	Almost Complete	Both EDGs failed to continue running 22 hours into 24-hour test due to a short on voltage suppression devices due to inadequate cooling in excitation cabinet.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
69	Test	Design	External Environment	Inst & Control	Governor	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
70	Test	Design	External Environment	Inst & Control	Governor	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
71	Test	Design	External Environment	Starting	Valve	1987	Failure to Start	Almost Complete	Air start solenoid valves were inoperable and prevented the EDGs from starting. This was due to accelerated degradation.
72	Test	Design	Internal to Component	Breaker	Switch	1992	Failure to Start	Partial	When the operator attempted to synchronize the emergency diesel generator to offsite power, the output breaker failed to close. The root cause of the EDG output breaker failure to close has been determined to be failure of a switch. A contact pair of the switch lost electrical continuity due to slight breaker movement and/or buildup of oxidation/pitting on the contact surfaces. Switches on all EDGs were replaced.
73	Test	Design	Internal to Component	Cooling	Valve	1980	Failure to Run	Complete	Faulty positioners on service water valves in the cooling sub-system led to a failure of all EDGs.
74	Test	Design	Internal to Component	Engine	Turbocharger	1983	Failure to Run	Partial	Vibration resulted in failure of the turbocharger mounting bolts.
75	Test	Design	Internal to Component	Engine	Sensors	1984	Failure to Run	Complete	EDG trips occurred due to an out of calibration temperature switch, leaking air start valve gasket, clearing of lube oil strainer, cleaning of air ejector, problem with air start distributor, out of calibration pressure switch and shattered/leaking piston.
76	Test	Design	Internal to Component	Engine	Governor	1982	Failure to Run	Complete	Failure of the electrical governors was caused by a burnt resistor in the power supply of the control units.
77	Test	Design	Internal to Component	Engine	Piston	1986	Failure to Run	Almost Complete	Failure of the piston wristpin bearings for four cylinders was due to inadequate lube oil film. The other EDG showed existence of similar problems.
78	Test	Design	Internal to Component	Inst & Control	Relay	1980	Failure to Start	Complete	During the performance of a pre-operational test, the safety injection signal to the EDGs was picked up. Both EDGs at one unit did not start.
79	Test	Design	Internal to Component	Inst & Control	Voltage Regulator	1982	Failure to Start	Partial	EDG tripped on overvoltage due to generator output voltage increasing too fast with respect to frequency. Setting on voltage regulator changed. Another EDG tripped on overvoltage due to an incorrect setting on the voltage regulator and a relay picking up lower than expected. Another EDG tripped due to failed speed sensing circuit device that is the frequency to voltage converter.
80	Test	Design	Internal to Component	Inst & Control	Piping	1980	Failure to Run	Partial	EDG tripped due to a fitting on the control air system vibrating loose, bleeding of holding pressure to the master shutdown valve. Another EDG tripped due to an air leak on the supply line fitting to fuel shutoff pistons causing the fuel control linkage to go to zero fuel position.
81	Test	Design	Internal to Component	Inst & Control	Sensors	1982	Failure to Run	Partial	One EDG was manually shut down on low water pressure alarm, and another EDG tripped on low cooling water pressure. Both failures were caused by a bad low cooling water pressure switch.
82	Test	Design	Internal to Component	Starting	Valve	1983	Failure to Start	Partial	EDGs failed to auto-start after tripping, due to the shutdown solenoid sticking in the shutdown position.
83	Test	Design	Internal to Component	Starting	Motor	1981	Failure to Start	Partial	Three EDGs air start motors failed to develop minimum rotational speed due to wear, dirt, and grit in the air start system.
84	Test	Design	Other	Generator	Voltage Regulator	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
85	Test	Design	Other	Generator	Load Sequencer	1981	Failure to Start	Partial	Agastat timer relays setpoint drift and faulty relays resulted in EDG failures.
86	Test	Design	Other	Generator	Voltage Regulator	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.
87	Test	Design	Other	Inst & Control	Governor	1991	Failure to Run	Partial	An EDG exhibited erratic load control due to intermittent failure of the governor electronic control unit; later, after returning to service, the other EDG tripped on reverse power also caused by failure of the governor control unit.
88	Test	Design	Other	Inst & Control	Relay	1982	Failure to Start	Almost Complete	This event resulted from intermittent failures of the diesel low lube oil pressure start time relay. The relay would prematurely time out before actual pressure was above the low trip setpoint during initial starting of the diesel. This occurred in three of four EDGs and was a failure-to-start. It was detected during testing.
89	Test	Environmental	Design/ Construction/ Manufacture/ Installation Inadequacy	Generator	Voltage Regulator	1990	Failure to Run	Almost Complete	EDG voltage regulator failed due to a partially failed transistor in the static exciter circuit. This was due to a high temperature in the control cabinet. Other EDG equipment susceptible to same conditions due to identical design.
90	Test	Environmental	External Environment	Cooling	Miscellaneous	1985	Failure to Start	Almost Complete	Due to exceptionally cold temperatures outside the EDG room, the cooling water temperature was too low. One EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. And another EDG was removed from maintenance and tested, when it then tripped on reverse power and engine vibration after starting.
91	Test	Environmental	External Environment	Inst & Control	Governor	1995	Failure to Run	Complete	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
92	Test	Environmental	External Environment	Inst & Control	Governor	1995	Failure to Run	Partial	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
93	Test	Environmental	External Environment	Inst & Control	Miscellaneous	1985	Failure to Run	Almost Complete	An EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. Another EDG tripped on reverse power and engine vibration, after starting. The cause was attributed to the cold outside temperature (-10 degrees F) with non-functioning outside air supply dampers causing low temperatures in the diesel bays. Also, the service water to the EDG governors was cold, causing sluggish performance. Corrective actions involved sealing the room from the weather.
94	Test	Environmental	Internal to Component	Cooling	Heat Exchanger	1982	Failure to Run	Partial	EDG cooling water inlet and outlet temperatures exceeded allowable valves, due to fouling of the cooling water heat exchanger tubes.
95	Test	Environmental	Internal to Component	Exhaust	Valve	1987	Failure to Run	Partial	There was a residue in the exhaust damper operator due to water in the instrument air system resulting in the failure of the dampers to open.
96	Test	Environmental	Internal to Component	Fuel Oil	Strainer	1988	Failure to Run	Partial	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores
97	Test	Environmental	Internal to Component	Fuel Oil	Strainer	1988	Failure to Run	Almost Complete	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
98	Test	Environmental	Internal to Component	Starting	Strainer	1985	Failure to Start	Almost Complete	EDG did not start because the fuel racks did not open to supply fuel before the 15-second incomplete sequence timer tripped off. Oil was found in the air start system and a residue of lubricant was on the starting air header filters. Similar conditions were found on the B EDG.
99	Test	Environmental	Internal to Component	Starting	Valve	1986	Failure to Start	Partial	Failure of air solenoid valves in the EDG air start systems to fully close due to corrosion products prevented the air-start motor from disengaging during starts.
100	Test	Environmental	Operational/ Human Error	Cooling	Heat Exchanger	1994	Failure to Run	Partial	Elevated temperatures and frequency swings were observed. Clogging of the heat exchangers by zebra mussels was the cause of the high temperatures. Inspection revealed 50% plugging.
101	Test	Environmental	Operational/ Human Error	Cooling	Heat Exchanger	1984	Failure to Run	Almost Complete	EDG overheated due to no cooling water flow caused by clam shells on the inlet tube sheet of the first cooler. No flow also found to other EDGs. Clam growth caused by inadequate chlorination, followed by high chlorination that released shells into the system.
102	Test	Maintenance	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Miscellaneous	1983	Failure to Run	Complete	Breakers tripped on over-current. Incorrect bulb-type indication was installed in the local panel.
103	Test	Maintenance	Internal to Component	Engine	Valve	1998	Failure to Run	Almost Complete	One EDG had broken exhaust valve insert and the other had a sticking exhaust valve. Both EDGs lost compression in the affected cylinder. Both EDGs ran for some time before failure to carry load.
104	Test	Maintenance	Internal to Component	Fuel Oil	Miscellaneous	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.
105	Test	Maintenance	Internal to Component	Fuel Oil	Pump	1983	Failure to Run	Partial	Fuel pump belts were broken due to normal wear.
106	Test	Maintenance	Internal to Component	Fuel Oil	Miscellaneous	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.
107	Test	Maintenance	Internal to Component	Generator	Power Resistor	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
108	Test	Maintenance	Internal to Component	Generator	Power Resistor	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
109	Test	Maintenance	Internal to Component	Generator	Power Resistor	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
110	Test	Maintenance	Internal to Component	Inst & Control	Valve	1991	Failure to Start	Almost Complete	Foreign material in air control system check valves caused shutdown of two EDGs.
111	Test	Maintenance	Internal to Component	Inst & Control	Fuse	1980	Failure to Start	Partial	EDG tripped on overspeed due to two blown control power fuses. Another EDG was inoperable when an inappropriate recorder caused a control power fuse to blow.
112	Test	Maintenance	Internal to Component	Inst & Control	Relay	1998	Failure to Start	Almost Complete	Both EDGs failed due to faulty starting sequence relays. Loose contacts and high contact resistance were the causes.
113	Test	Maintenance	Internal to Component	Inst & Control	Relay	1982	Failure to Start	Partial	EDG speed could not be manually increased due to a slightly dirty contact on the mode switch or relay. Another EDG start circuit failed due to a speed-sensing relay burned contact stuck in closed position.
114	Test	Maintenance	Internal to Component	Starting	Miscellaneous	1982	Failure to Start	Almost Complete	There were nine air start problems on an EDG. Problems ranged from low pressure to air start valve failures and occurred on all three diesel generators.
115	Test	Maintenance	Operational/ Human Error	Breaker	Switch	1984	Failure to Start	Complete	All of the EDGs at one unit did not automatically start due to a misalignment during breaker line-up. The wrong DC knife switches were opened, thereby failing the EDG start relays.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
116	Test	Maintenance	Operational/ Human Error	Engine	Piston	1989	Failure to Run	Partial	Piston rings failed due to inadequate maintenance procedures.
117	Test	Maintenance	Operational/ Human Error	Fuel Oil	Valve	1986	Failure to Run	Almost Complete	The fuel strainer valves on multiple EDGs were misaligned, thereby restricting fuel oil to the EDGs.
118	Test	Maintenance	Operational/ Human Error	Fuel Oil	Strainer	1986	Failure to Run	Partial	Maintenance personnel failed to check the fuel filters which led to the failure of one EDG with a plugged filter.
119	Test	Maintenance	Operational/ Human Error	Fuel Oil	Tank	1996	Failure to Run	Partial	Water in fuel oil exceeded tech spec limits for both EDGs.
120	Test	Maintenance	Operational/ Human Error	Fuel Oil	Fuel Rack	1990	Failure to Start	Complete	Fuel rack binding of the fuel rack pivot points was caused by paint, which occurred during painting of the EDGs. The same problem was found on the other EDG, which had been painted at the same time.
121	Test	Maintenance	Operational/ Human Error	Fuel Oil	Piping	1983	Failure to Run	Partial	Maintenance personnel damaged fuel oil tubing, thereby causing leaks.
122	Test	Maintenance	Operational/ Human Error	Inst & Control	Relay	1987	Failure to Run	Complete	One EDG stopped during a test run due to an incorrect setpoint on a newly installed phase differential overcurrent relay. Both EDGs had the same setpoint.
123	Test	Maintenance	Operational/ Human Error	Inst & Control	Load Sequencer	1981	Failure to Start	Complete	Shutdown sequencers to both EDGs failed during testing. One EDG failed due to dirty contacts. The other EDG failed due to a sticking clutch. Both failures were attributed to maintenance and test equipment.
124	Test	Maintenance	Operational/ Human Error	Starting	Motor	1993	Failure to Start	Almost Complete	A test procedure required operators to apply air to the distributor while the EDG was running, resulting in damage to the air distributor such that the EDG would not start.
125	Test	Maintenance	Other	Battery	Battery	1981	Failure to Run	Partial	During surveillance tests, the batteries to both EDGs failed their surveillance tests. The test failures were due to low specific gravity.
126	Test	Operational	Operational/ Human Error	Cooling	Valve	1990	Failure to Run	Almost Complete	Service water throttle valves were not open enough because the reference used by operators was different from the reference used by engineering staff during flow balances.
127	Test	Operational	Operational/ Human Error	Generator	Logic Circuit	1982	Failure to Start	Almost Complete	The operator turned the governor controller in the decrease speed direction while paralleling to the bus; that tripped the EDG on reverse power when the operator failed to open the diesel output breaker prior to reaching the reverse power setpoint.
128	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Turbocharger	1995	Failure to Run	Complete	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
129	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Turbocharger	1995	Failure to Run	Partial	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
130	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Shaft	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.

Item	Discovery Method	Coupling Factor	Proximate Cause	Sub-System	Piece Part	Year	Failure Mode	Degree of Failure	Description
131	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Engine	Shaft	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.
132	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Exhaust	Valve	1991	Failure to Run	Partial	The exhaust damper roll pins failed resulting in the failure of the dampers to open. The cause of pin failure determined to be a manufacturing error.
133	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Governor	1992	Failure to Run	Partial	Performing EDG monthly load test when governor instabilities noticed. Air trapped in the governor compensation system caused vibrations.
134	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Generator Excitation	1994	Failure to Start	Partial	Both EDGs were found incapable of carrying design load. Previous governor modifications were identified as the cause. A misadjusted engine governor output linkage and engine performance degradation limited the EDG output.
135	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Inst & Control	Relay	1991	Failure to Start	Partial	A 240/480 Vac starting contactor coil was in systems designed for 250VDC, which caused control relay arcing across contacts preventing an automatic restart of the EDGs.
136	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Valve	1990	Failure to Start	Partial	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.
137	Test	Quality	Design/ Construction/ Manufacture/ Installation Inadequacy	Starting	Valve	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.
138	Test	Quality	Internal to Component	Breaker	Relay	1993	Failure to Start	Partial	The EDG output breaker tripped on reverse power. The EDG tripped on reverse power due to a faulty reverse power relay; the relay was replaced on all EDGs.

Appendix B

Data Summary by Sub-System

Appendix B

Data Summary by Sub-System

This appendix is a summary of the data evaluated in the common-cause failure (CCF) data collection effort for EDGs. The table in this appendix supports the sections in Chapter 4. The table is sorted alphabetically, by the first four columns.

Table B-1. EDG CCF event summary, sorted by sub-system.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
1	Battery	Other	Test	Battery	Maintenance	1981	Failure to Run	Partial	During surveillance tests, the batteries to both EDGs failed their surveillance tests. The test failures were due to low specific gravity.
2	Breaker	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Logic Circuit	Design	1988	Failure to Start	Almost Complete	A faulty switch contact and incorrect logic circuit design prevented three EDG output breakers from closing. Switches on all EDGs were replaced.
3	Breaker	Internal to Component	Demand	Switch	Quality	1987	Failure to Start	Almost Complete	The output breaker would not close due to a deformed spring retainer, which prevented a cell switch from providing the permissive to close the breaker.
4	Breaker	Internal to Component	Inspection	Relay	Design	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
5	Breaker	Internal to Component	Inspection	Relay	Design	1987	Failure to Run	Partial	EDG output breakers on two units should not have had instantaneous over-current protection. This condition could have caused the EDG output breakers to trip before the load breaker would open on a fault.
6	Breaker	Internal to Component	Maintenance	Logic Circuit	Design	1986	Failure to Start	Partial	Diesel generator output breakers failed to close during a surveillance check.
7	Breaker	Internal to Component	Test	Relay	Quality	1993	Failure to Start	Partial	The EDG output breaker tripped on reverse power. The EDG tripped on reverse power due to a faulty reverse power relay; the relay was replaced on all EDGs.
8	Breaker	Internal to Component	Test	Switch	Design	1992	Failure to Start	Partial	When the operator attempted to synchronize the emergency diesel generator to offsite power, the output breaker failed to close. The root cause of the EDG output breaker failure to close has been determined to be failure of a switch. A contact pair of the switch lost electrical continuity due to slight breaker movement and/or buildup of oxidation/pitting on the contact surfaces. Switches on all EDGs were replaced.
9	Breaker	Operational/ Human Error	Demand	Relay	Maintenance	1991	Failure to Start	Almost Complete	The EDGs did not automatically pick up the load of the 480V busses because the unit trip lockout relays were reset.
10	Breaker	Operational/ Human Error	Test	Switch	Maintenance	1984	Failure to Start	Complete	All of the EDGs at one unit did not automatically start due to a misalignment during breaker line-up. The wrong DC knife switches were opened, thereby failing the EDG start relays.
11	Cooling	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Miscellaneous	Design	1997	Failure to Run	Partial	Emergency Diesel Generators testing identified elevated EDG radiator, control and engine room air temperatures. This increase is due to a portion of the radiator discharge air released to atmosphere from the roof of each EDG building being recirculated back into the EDG radiator room.
12	Cooling	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Piping	Design	1988	Failure to Run	Partial	EDG configuration of a diffuser plate allowed sufficient movement to initiate fatigue failure. After failure, the plate contacted the intercooler tubes causing fretting.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
13	Cooling	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Piping	Design	1995	Failure to Run	Almost Complete	Both EDGs failed surveillance test runs due to overheating of the governor oil. Insufficient cooling flow was available because of a design error in pipe size.
14	Cooling	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Pump	Design	1996	Failure to Run	Almost Complete	Inadequate design left exposed cooling water piping, which freezes in winter.
15	Cooling	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Valve	Design	1988	Failure to Run	Partial	High lube oil temperature was caused by failed power elements in temperature control valves.
16	Cooling	External Environment	Inspection	Heat Exchanger	Environmental	1995	Failure to Run	Partial	Epoxy paint detached from the inside of the cooling water piping and plugged the heat exchanger.
17	Cooling	External Environment	Test	Miscellaneous	Environmental	1985	Failure to Start	Almost Complete	Due to exceptionally cold temperatures outside the EDG room, the cooling water temperature was too low. One EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. And another EDG was removed from maintenance and tested, when it then tripped on reverse power and engine vibration after starting.
18	Cooling	External Environment	Test	Piping	Design	1990	Failure to Run	Almost Complete	Two of three of the emergency diesel generators had a jacket water leak due to a nipple failure. The cause of the crack has been attributed to a vibration-induced fatigue.
19	Cooling	Internal to Component	Demand	Valve	Maintenance	1981	Failure to Run	Almost Complete	EDG cooling water check valves malfunctioned, resulting in a loss of cooling.
20	Cooling	Internal to Component	Test	Heat Exchanger	Environmental	1982	Failure to Run	Partial	EDG cooling water inlet and outlet temperatures exceeded allowable valves, due to fouling of the cooling water heat exchanger tubes.
21	Cooling	Internal to Component	Test	Valve	Design	1980	Failure to Run	Complete	Faulty positioners on service water valves in the cooling sub-system led to a failure of all EDGs.
22	Cooling	Operational/ Human Error	Maintenance	Valve	Maintenance	1993	Failure to Run	Complete	Incorrect installation of pilot solenoid valves was caused by a lack of procedural adherence due to personnel error. Contributing causes were procedural inadequacies, inattention to detail, and inadequate skills.
23	Cooling	Operational/ Human Error	Test	Heat Exchanger	Environmental	1984	Failure to Run	Almost Complete	EDG overheated due to no cooling water flow caused by clam shells on the inlet tube sheet of the first cooler. No flow also found to other EDGs. Clam growth caused by inadequate chlorination, followed by high chlorination that released shells into the system.
24	Cooling	Operational/ Human Error	Test	Heat Exchanger	Environmental	1994	Failure to Run	Partial	Elevated temperatures and frequency swings were observed. Clogging of the heat exchangers by zebra mussels was the cause of the high temperatures. Inspection revealed 50% plugging.
25	Cooling	Operational/ Human Error	Test	Valve	Operational	1990	Failure to Run	Almost Complete	Service water throttle valves were not open enough because the reference used by operators was different from the reference used by engineering staff during flow balances.
26	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Bearing	Operational	1981	Failure to Run	Partial	A crankshaft bearing was wiped and another crankshaft bearing had a crack. Extended operations could cause bearing failure. The wiped journal surface was caused by high temperature from inadequate lubrication.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
27	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Fuel Nozzles	Quality	1991	Failure to Run	Partial	Cracked fuel injector nozzle tips were found in EDGs. The cracks were due to inadequate ligament thickness and excessive nitriding depth.
28	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Valve	Design	1997	Failure to Start	Partial	Valve adjustment assemblies cracked, manufacturing defect.
29	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Maintenance	Shaft	Design	1986	Failure to Run	Partial	The floating bushing of the idler gear was found with small cracks and frozen to the stub shaft on one EDG, and found with a through-wall crack on another EDG. Cracks were caused by fast starts without full main lube oil pressure, due to the design of the system.
30	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Miscellaneous	Design	1990	Failure to Run	Partial	All three EDGs were underrated for full emergency design loads. Previous testing did not detect the problem due to relatively low ambient temperatures.
31	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Piping	Design	1995	Failure to Run	Partial	A leak was detected in the jacket water cooling system. A system fitting had failed as a result of an inadequate design. Vibration fatigue resulted in cracking.
32	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Shaft	Quality	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.
33	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Shaft	Quality	1994	Failure to Start	Partial	Magnetic pickup target gear shaft failed during load test. A manufacturer defect in the shaft caused the failure. The unit swing diesel had the same component installed and the same part was replaced on all diesels at both units.
34	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Turbocharger	Quality	1995	Failure to Run	Complete	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.
35	Engine	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Turbocharger	Quality	1995	Failure to Run	Partial	A turbo-charger failed during operability testing. A fan blade failed due to vibration. The fan had just been replaced on all units. A turbo wall insert from a different source had been judged suitable but resulted in this failure. Parts were replaced on EDGs at both units.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
36	Engine	Internal to Component	Inspection	Fuel Rack	Design	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.
37	Engine	Internal to Component	Inspection	Fuel Rack	Design	1983	Failure to Run	Partial	Air leakage of the fuel rack assembly was due to a leak through a hole in the exhaust valve diaphragm.
38	Engine	Internal to Component	Inspection	Fuel Rack	Design	1981	Failure to Run	Partial	Failure of a taper pin in the fuel rack assembly occurred.
39	Engine	Internal to Component	Test	Governor	Design	1982	Failure to Run	Complete	Failure of the electrical governors was caused by a burnt resistor in the power supply of the control units.
40	Engine	Internal to Component	Test	Piston	Design	1986	Failure to Run	Almost Complete	Failure of the piston wristpin bearings for four cylinders was due to inadequate lube oil film. The other EDG showed existence of similar problems.
41	Engine	Internal to Component	Test	Sensors	Design	1984	Failure to Run	Complete	EDG trips occurred due to an out of calibration temperature switch, leaking air start valve gasket, clearing of lube oil strainer, cleaning of air ejector, problem with air start distributor, out of calibration pressure switch and shattered/leaking piston.
42	Engine	Internal to Component	Test	Turbocharger	Design	1983	Failure to Run	Partial	Vibration resulted in failure of the turbocharger mounting bolts.
43	Engine	Internal to Component	Test	Valve	Maintenance	1998	Failure to Run	Almost Complete	One EDG had broken exhaust valve insert and the other had a sticking exhaust valve. Both EDGs lost compression in the affected cylinder. Both EDGs ran for some time before failure to carry load.
44	Engine	Operational/ Human Error	Inspection	Bearing	Maintenance	1980	Failure to Run	Partial	The EDG lower crankshaft main thrust bearing was found wiped due to low lube oil level. Subsequent inspection of other EDG revealed same problem. Dipstick markings were changed.
45	Engine	Operational/ Human Error	Inspection	Piston	Maintenance	1990	Failure to Run	Partial	Sand was found in the lube oil due to sandblasting where the sand entered through the intake. This event led to scoring of the cylinder walls.
46	Engine	Operational/ Human Error	Test	Piston	Maintenance	1989	Failure to Run	Partial	Piston rings failed due to inadequate maintenance procedures.
47	Exhaust	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Valve	Quality	1991	Failure to Run	Partial	The exhaust damper roll pins failed resulting in the failure of the dampers to open. The cause of pin failure determined to be a manufacturing error.
48	Exhaust	Internal to Component	Test	Valve	Environmental	1987	Failure to Run	Partial	There was a residue in the exhaust damper operator due to water in the instrument air system resulting in the failure of the dampers to open.
49	Fuel Oil	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Tank	Design	1994	Failure to Run	Partial	Inaccurate level instrumentation resulted in less than required fuel inventory. A design error in level instruments was identified. Contributing factors included human error and procedural deficiencies.
50	Fuel Oil	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Pump	Design	1998	Failure to Start	Almost Complete	EDGs fail to start. The cause of the failure was loss of pump prime due to air entering around the fuel oil booster pump shaft seals.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
51	Fuel Oil	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Pump	Design	1991	Failure to Run	Partial	There was a cracked fitting on a fuel oil pump. The cause of the event was attributed to the delivery valve holder design, which is prone to cracking.
52	Fuel Oil	External Environment	Test	Piping	Design	1981	Failure to Run	Complete	EDG fuel supply hose developed a leak due to excessive localized flexure and vibration. Following repair, EDG tripped due to low control air pressure caused by fitting loosened by engine vibration. Another EDG fuel injector supply line failed due to metal fatigue and vibration.
53	Fuel Oil	Internal to Component	Demand	Pump	Design	1983	Failure to Run	Partial	Minor fuel oil leaks occurred on pumps.
54	Fuel Oil	Internal to Component	Test	Miscellaneous	Maintenance	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.
55	Fuel Oil	Internal to Component	Test	Miscellaneous	Maintenance	1981	Failure to Start	Partial	Numerous gaskets, seals check valves, fittings, and "O" rings leaked or failed.
56	Fuel Oil	Internal to Component	Test	Pump	Maintenance	1983	Failure to Run	Partial	Fuel pump belts were broken due to normal wear.
57	Fuel Oil	Internal to Component	Test	Strainer	Environmental	1988	Failure to Run	Almost Complete	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores
58	Fuel Oil	Internal to Component	Test	Strainer	Environmental	1988	Failure to Run	Partial	EDG load decreased due to high differential pressure across the primary fuel oil filter due to clogging by fungus. All EDG day tanks and main storage tanks contained fungus and fungus spores
59	Fuel Oil	Operational/ Human Error	Demand	Pump	Maintenance	1993	Failure to Run	Partial	Fuel oil transfer pump for EDG did not start due to a blown fuse. The fuel oil transfer pump for another EDG was also failed due to a metal piece found between contacts in the low-level cutoff switch.
60	Fuel Oil	Operational/ Human Error	Inspection	Pump	Maintenance	1994	Failure to Run	Almost Complete	Fuel transfer pumps were inoperable due to improper greasing of motor bearings during cold weather operations.
61	Fuel Oil	Operational/ Human Error	Inspection	Tank	Maintenance	1986	Failure to Run	Complete	An operator drained all fuel oil day tanks while sampling the fuel oil.
62	Fuel Oil	Operational/ Human Error	Inspection	Valve	Maintenance	1983	Failure to Run	Complete	Both fuel oil valves were closed during transfers of fuel, isolating the normal supply from the respective fuel transfer pumps to each of the day tanks.
63	Fuel Oil	Operational/ Human Error	Test	Fuel Rack	Maintenance	1990	Failure to Start	Complete	Fuel rack binding of the fuel rack pivot points was caused by paint, which occurred during painting of the EDGs. The same problem was found on the other EDG, which had been painted at the same time.
64	Fuel Oil	Operational/ Human Error	Test	Piping	Maintenance	1983	Failure to Run	Partial	Maintenance personnel damaged fuel oil tubing, thereby causing leaks.
65	Fuel Oil	Operational/ Human Error	Test	Strainer	Maintenance	1986	Failure to Run	Partial	Maintenance personnel failed to check the fuel filters which led to the failure of one EDG with a plugged filter.
66	Fuel Oil	Operational/ Human Error	Test	Tank	Maintenance	1996	Failure to Run	Partial	Water in fuel oil exceeded tech spec limits for both EDGs.
67	Fuel Oil	Operational/ Human Error	Test	Valve	Maintenance	1986	Failure to Run	Almost Complete	The fuel strainer valves on multiple EDGs were misaligned, thereby restricting fuel oil to the EDGs.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
68	Generator	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Rotor	Quality	1985	Failure to Run	Almost Complete	Cracks were found in the interpolar connections of the damper windings on the rotor poles of the generator. One of the connectors broke during overspeed testing causing substantial damage to the stator. These connectors were not necessary, so they were removed on both generators.
69	Generator	Design/ Construction/ Manufacture/ Installation Inadequacy	Maintenance	Generator Excitation	Design	1985	Failure to Start	Partial	There was material incompatibility in the voltage regulator.
70	Generator	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Relay	Design	1991	Failure to Run	Partial	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.
71	Generator	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Relay	Design	1991	Failure to Run	Almost Complete	EDG load was observed to be exceeding the desired operating band. The electrical wiring diagram was found to be in error, resulting in improperly wired relays.
72	Generator	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Rotor	Design	1984	Failure to Run	Partial	A design fault in application of insulation led to rotor damage.
73	Generator	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Voltage Regulator	Design	1991	Failure to Start	Partial	Due to the sizing of the power potential transformers and the current transformers, there existed a small area within the leading kVAR range of the generator capability curve in which the voltage regulator would not function.
74	Generator	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Voltage Regulator	Environmental	1990	Failure to Run	Almost Complete	EDG voltage regulator failed due to a partially failed transistor in the static exciter circuit. This was due to a high temperature in the control cabinet. Other EDG equipment susceptible to same conditions due to identical design.
75	Generator	External Environment	Test	Generator Excitation	Design	1993	Failure to Run	Almost Complete	Both EDGs failed to continue running 22 hours into 24-hour test due to a short on voltage suppression devices due to inadequate cooling in excitation cabinet.
76	Generator	Internal to Component	Test	Power Resistor	Maintenance	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
77	Generator	Internal to Component	Test	Power Resistor	Maintenance	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.
78	Generator	Internal to Component	Test	Power Resistor	Maintenance	1987	Failure to Start	Partial	Incomplete sequence/underfrequency was caused by a defective power resistor overheating and premature failure due to fatigue.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
79	Generator	Operational/ Human Error	Test	Logic Circuit	Operational	1982	Failure to Start	Almost Complete	The operator turned the governor controller in the decrease speed direction while paralleling to the bus; that tripped the EDG on reverse power when the operator failed to open the diesel output breaker prior to reaching the reverse power setpoint.
80	Generator	Other	Maintenance	Casing	Design	1982	Failure to Run	Partial	Air baffle deformation due to overheating by space heaters caused EDG trips.
81	Generator	Other	Test	Load Sequencer	Design	1981	Failure to Start	Partial	Agastat timer relays setpoint drift and faulty relays resulted in EDG failures.
82	Generator	Other	Test	Voltage Regulator	Design	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.
83	Generator	Other	Test	Voltage Regulator	Design	1982	Failure to Run	Almost Complete	EDGs tripped on loss of field after being started. Reactive load change caused a loss of field/reverse power trip.
84	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Demand	Governor	Design	1987	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
85	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Demand	Governor	Design	1987	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
86	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Demand	Relay	Quality	1984	Failure to Start	Complete	Relay trips were caused by failed zener diodes in surge protection, which had been installed backwards. The relays were replaced with relays without zener diodes.
87	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Miscellaneous	Maintenance	1991	Failure to Start	Almost Complete	One EDG failed to start due to a defective crimp. Defective crimps were found in the other EDGs. Inadequate training, procedures, and QA.
88	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Relay	Design	1995	Failure to Start	Almost Complete	A wiring error was discovered, which would prevent the EDG output breakers from closing to a de-energized bus. The error in wiring was the result of an incorrect drawing in a design modification package.
89	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Maintenance	Sensors	Design	1988	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
90	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Maintenance	Sensors	Design	1988	Failure to Run	Complete	CCF events occurred at multiple units at a single plant site (actual failure at one unit, and a design flaw was detected before causing failure at the other unit). Due to a design flaw, numerous pressure sensor malfunctions occurred at both units.
91	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Fuse	Design	1992	Failure to Start	Complete	A simulated CO2 actuation blew the fuse in the EDG control panel. The condition resulted from a design deficiency during installation of the CO2 system.
92	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Generator Excitation	Quality	1994	Failure to Start	Partial	Both EDGs were found incapable of carrying design load. Previous governor modifications were identified as the cause. A misadjusted engine governor output linkage and engine performance degradation limited the EDG output.
93	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Governor	Quality	1992	Failure to Run	Partial	Performing EDG monthly load test when governor instabilities noticed. Air trapped in the governor compensation system caused vibrations.
94	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Load Sequencer	Design	1993	Failure to Start	Complete	Diesel sequencers did not load during test. The cause was inadequate design understanding and inadequate post-modification testing.
95	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Miscellaneous	Design	1985	Failure to Run	Partial	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
96	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Miscellaneous	Design	1985	Failure to Run	Almost Complete	CCF events occurred at multiple units at a single plant site. The hydraulic actuator of an EDG malfunctioned causing it to trip on overspeed. The cause of the failure was that sealant had blocked oil passageways to the actuator.
97	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Miscellaneous	Maintenance	1983	Failure to Run	Complete	Breakers tripped on over-current. Incorrect bulb-type indication was installed in the local panel.
98	Inst & Control	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Relay	Quality	1991	Failure to Start	Partial	A 240/480 Vac starting contactor coil was in systems designed for 250VDC, which caused control relay arcing across contacts preventing an automatic restart of the EDGs.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
99	Inst & Control	External Environment	Test	Governor	Environmental	1995	Failure to Run	Partial	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
100	Inst & Control	External Environment	Test	Governor	Design	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
101	Inst & Control	External Environment	Test	Governor	Environmental	1995	Failure to Run	Complete	Both EDGs failed surveillance test due to unreliable load control. Relay sockets were found degraded, causing high resistance connections. The failures were induced by vibration and found in numerous relay sockets. All sockets were replaced on both Units 1 and 2.
102	Inst & Control	External Environment	Test	Governor	Design	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Speed oscillations occurred on a EDG, following a startup without loading, due to a failed resistor in the governor unit. Similar conditions were found on the other EDGs. The cause was long-term heat fatigue.
103	Inst & Control	External Environment	Test	Miscellaneous	Environmental	1985	Failure to Run	Almost Complete	An EDG tripped on low oil pressure and high vibration. Another EDG tripped on overvoltage. Another EDG tripped on reverse power and engine vibration, after starting. The cause was attributed to the cold outside temperature (-10 degrees F) with non-functioning outside air supply dampers causing low temperatures in the diesel bays. Also, the service water to the EDG governors was cold, causing sluggish performance. Corrective actions involved sealing the room from the weather.
104	Inst & Control	Internal to Component	Demand	Relay	Design	1980	Failure to Start	Complete	During attempts to shutdown the EDGs, the lockout relays were damaged, thereby making the EDGs inoperable.
105	Inst & Control	Internal to Component	Test	Fuse	Maintenance	1980	Failure to Start	Partial	EDG tripped on overspeed due to two blown control power fuses. Another EDG was inoperable when an inappropriate recorder caused a control power fuse to blow.
106	Inst & Control	Internal to Component	Test	Piping	Design	1980	Failure to Run	Partial	EDG tripped due to a fitting on the control air system vibrating loose, bleeding of holding pressure to the master shutdown valve. Another EDG tripped due to an air leak on the supply line fitting to fuel shutoff pistons causing the fuel control linkage to go to zero fuel position.
107	Inst & Control	Internal to Component	Test	Relay	Design	1980	Failure to Start	Complete	During the performance of a pre-operational test, the safety injection signal to the EDGs was picked up. Both EDGs at one unit did not start.
108	Inst & Control	Internal to Component	Test	Relay	Maintenance	1982	Failure to Start	Partial	EDG speed could not be manually increased due to a slightly dirty contact on the mode switch or relay. Another EDG start circuit failed due to a speed-sensing relay burned contact stuck in closed position.
109	Inst & Control	Internal to Component	Test	Relay	Maintenance	1998	Failure to Start	Almost Complete	Both EDGs failed due to faulty starting sequence relays. Loose contacts and high contact resistance were the causes.
110	Inst & Control	Internal to Component	Test	Sensors	Design	1982	Failure to Run	Partial	One EDG was manually shut down on low water pressure alarm, and another EDG tripped on low cooling water pressure. Both failures were caused by a bad low cooling water pressure switch.
111	Inst & Control	Internal to Component	Test	Valve	Maintenance	1991	Failure to Start	Almost Complete	Foreign material in air control system check valves caused shutdown of two EDGs.
112	Inst & Control	Internal to Component	Test	Voltage Regulator	Design	1982	Failure to Start	Partial	EDG tripped on overvoltage due to generator output voltage increasing too fast with respect to frequency. Setting on voltage regulator changed. Another EDG tripped on overvoltage due to an incorrect setting on the voltage regulator and a relay picking up lower than expected. Another EDG tripped due to failed speed sensing circuit device that is the frequency to voltage converter.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
113	Inst & Control	Operational/ Human Error	Demand	Governor	Maintenance	1991	Failure to Start	Almost Complete	Inadequate post maintenance testing was performed following replacement of the governor. This was due to a cognitive error on the part of utility personnel in that an approved work order step, which specified a fast start test of the EDG, was not performed.
114	Inst & Control	Operational/ Human Error	Demand	Relay	Design	1980	Failure to Start	Complete	During surveillance testing, the operator mistakenly caused a blackout signal, causing all EDGs to start. EDGs were stopped, but during restoration process, all were inoperable for approximately 10 minutes.
115	Inst & Control	Operational/ Human Error	Demand	Relay	Design	1980	Failure to Start	Complete	All EDGs started on an inadvertent SIAS (technician error) during testing. The licensed operator stopped the EDGs prior to the SIAS reset, causing EDGs to be inoperable.
116	Inst & Control	Operational/ Human Error	Inspection	Fuse	Maintenance	1990	Failure to Start	Partial	Control power fuses were blown on EDG due to poor maintenance practices and less than adequate documentation of the jacket water system and pressure switch.
117	Inst & Control	Operational/ Human Error	Inspection	Governor	Operational	1987	Failure to Start	Almost Complete	Inadequate operating procedures resulted in EDG failures. The load limit knob was not returned to the correct maximum setting following a special test on both EDGs due to mis-communication.
118	Inst & Control	Operational/ Human Error	Inspection	Relay	Maintenance	1984	Failure to Start	Partial	A review of the protective relay calibration sheet identified that both EDG differential relays were out-of-tolerance.
119	Inst & Control	Operational/ Human Error	Maintenance	Sensors	Maintenance	1983	Failure to Run	Partial	An EDG tripped on reverse current twice during operability testing and another EDG tripped on reverse current once. The cause was attributed to a procedural inadequacy that did not help the operator in avoiding a reverse current trip.
120	Inst & Control	Operational/ Human Error	Test	Load Sequencer	Maintenance	1981	Failure to Start	Complete	Shutdown sequencers to both EDGs failed during testing. One EDG failed due to dirty contacts. The other EDG failed due to a sticking clutch. Both failures were attributed to maintenance and test equipment.
121	Inst & Control	Operational/ Human Error	Test	Relay	Maintenance	1987	Failure to Run	Complete	One EDG stopped during a test run due to an incorrect setpoint on a newly installed phase differential overcurrent relay. Both EDGs had the same setpoint.
122	Inst & Control	Other	Inspection	Fuse	Design	1982	Failure to Start	Partial	An EDG power fuse in the control circuitry blew when a broken lead on the annunciator horn shorted to the case. Another EDG power fuse blew, when a burned out bulb on the control board was replaced and the new bulb shattered, thereby shorting the filaments.
123	Inst & Control	Other	Test	Governor	Design	1991	Failure to Run	Partial	An EDG exhibited erratic load control due to intermittent failure of the governor electronic control unit; later, after returning to service, the other EDG tripped on reverse power also caused by failure of the governor control unit.
124	Inst & Control	Other	Test	Relay	Design	1982	Failure to Start	Almost Complete	This event resulted from intermittent failures of the diesel low lube oil pressure start time relay. The relay would prematurely time out before actual pressure was above the low trip setpoint during initial starting of the diesel. This occurred in three of four EDGs and was a failure-to-start. It was detected during testing.
125	Lube Oil	External Environment	Inspection	Heat Exchanger	Design	1981	Failure to Run	Partial	The lube-oil sub-system was contaminated by lube oil coolers leaking water into the lube oil.
126	Lube Oil	Operational/ Human Error	Inspection	Tank	Maintenance	1989	Failure to Run	Almost Complete	Degradation of the EDG lube oil occurred. This was due to the procedure not requiring the immersion heater to be shut off.
127	Lube Oil	Other	Inspection	Check Valve	Design	1996	Failure to Start	Partial	Leaking lube oil check valves render EDGs inoperable.
128	Starting	Design/ Construction/ Manufacture/ Installation Inadequacy	Inspection	Valve	Design	1994	Failure to Start	Partial	The air regulator setpoint drifted up. The cause was attributed to selection of the wrong component. All regulators were replaced with a different model.

Item	Sub-System	Proximate Cause	Discovery Method	Piece Part	Coupling Factor	Year	Failure Mode	Degree of Failure	Description
129	Starting	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Valve	Quality	1990	Failure to Start	Partial	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.
130	Starting	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Valve	Quality	1990	Failure to Start	Almost Complete	CCF events occurred at multiple units at a single plant site. Air valve pistons sticking prevented the EDGs from starting, because of inadequate manufacturing tolerances.
131	Starting	Design/ Construction/ Manufacture/ Installation Inadequacy	Test	Valve	Design	1998	Failure to Start	Partial	EDG potential for a start failure due to the air start solenoid valves not operating consistently below 90 vdc and below 200 psig
132	Starting	External Environment	Test	Valve	Design	1987	Failure to Start	Almost Complete	Air start solenoid valves were inoperable and prevented the EDGs from starting. This was due to accelerated degradation.
133	Starting	Internal to Component	Test	Miscellaneous	Maintenance	1982	Failure to Start	Almost Complete	There were nine air start problems on an EDG. Problems ranged from low pressure to air start valve failures and occurred on all three diesel generators.
134	Starting	Internal to Component	Test	Motor	Design	1981	Failure to Start	Partial	Three EDGs air start motors failed to develop minimum rotational speed due to wear, dirt, and grit in the air start system.
135	Starting	Internal to Component	Test	Strainer	Environmental	1985	Failure to Start	Almost Complete	EDG did not start because the fuel racks did not open to supply fuel before the 15-second incomplete sequence timer tripped off. Oil was found in the air start system and a residue of lubricant was on the starting air header filters. Similar conditions were found on the B EDG.
136	Starting	Internal to Component	Test	Valve	Environmental	1986	Failure to Start	Partial	Failure of air solenoid valves in the EDG air start systems to fully close due to corrosion products prevented the air-start motor from disengaging during starts.
137	Starting	Internal to Component	Test	Valve	Design	1983	Failure to Start	Partial	EDGs failed to auto-start after tripping, due to the shutdown solenoid sticking in the shutdown position.
138	Starting	Operational/ Human Error	Test	Motor	Maintenance	1993	Failure to Start	Almost Complete	A test procedure required operators to apply air to the distributor while the EDG was running, resulting in damage to the air distributor such that the EDG would not start.

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10. SUPPLEMENTARY NOTES

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11. ABSTRACT (200 words or less)

This report documents a study performed on the set of common-cause failures (CCF) of emergency diesel generators (EDG) from 1980 to 2000. The data studied here were derived from the NRC CCF database, which is based on US commercial nuclear power plant event data. This report is the result of an in-depth review of the EDG CCF data and presents several insights about the EDG CCF data. The objective of this document is to look beyond the CCF parameter estimates that can be obtained from the CCF data, to gain further understanding of why CCF events occur and what measures may be taken to prevent, or at least mitigate the effect of, EDG CCF events. This report presents quantitative presentation of the EDG CCF data and discussion of some engineering aspects of the EDG events.

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